**CLOSED-ECONOMY MULTIPLE-SCHEDULE
PERFORMANCE: EFFECTS OF DEPRIVATION AND
SESSION DURATION**

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Three pigeons responded for food reinforcement on multiple variable-interval schedules in which the total consumption of food was entirely determined by the subjects' interaction with the schedules (a closed economy). The finding of overmatching, where response allocation between components is more extreme than the distribution of reinforcers, was reconfirmed. Generalized-matching sensitivity decreased from overmatching to undermatching values typical of conventional multiple schedules when food deprivation was increased by decreasing session duration, but not when deprivation was increased by decreasing overall reinforcer rate. Sensitivity also increased from undermatching to overmatching as session duration increased from 100 min to 24 hr, while deprivation was held constant by decreasing overall reinforcer rate. These results can be understood in terms of increases in the value of extraneous reinforcers relative to food reinforcers as deprivation decreases or as the economy for extraneous reinforcers becomes more closed. However, no published quantitative expression of the effects of extraneous reinforcers is entirely consistent with the results.

Key words: multiple schedules, overmatching, closed economy, deprivation, extraneous reinforcement, session duration, Herrnstein's equation, key peck, pigeons

Performance on multiple variable-interval (VI) schedules can be described by the generalized matching law (Baum, 1974):

$$\frac{B_1}{B_2} = c \left(\frac{R_1}{R_2} \right)^a, \quad (1)$$

where B and R respectively denote the rates at which responses are emitted and reinforcers are obtained in Components 1 and 2 of the multiple schedule. The parameter c measures bias towards one or the other component, and typically approximates 1.0 (McSweeney, Farmer, Dougan, & Whipple, 1986). The parameter a is called sensitivity to reinforcement, and measures the extent to which changes in the component reinforcer ratio are reflected in the response ratio. If $a = 1.0$, the allocation of the responding between components strictly matches the distribution of reinforcers. If $a < 1.0$, response allocation is said to undermatch the distribution of reinforcers. Undermatching characterizes the

majority of published multiple-schedule experiments (McSweeney et al.).

Elliffe and Davison (1985) reported consistent overmatching ($a > 1.0$) in an experiment in which pigeons received their total intake of food as reinforcers for responding on multiple schedules available 24 hr per day. Such a situation is called a closed economy (Hursh, 1980, 1984), in contrast with the more commonly arranged open economy, in which subjects are maintained at a constant level of food deprivation by supplementary food given outside the experimental session. Elliffe and Davison's mean a value, across 3 pigeons, was 1.57, in comparison with McSweeney et al.'s median a value across open-economy experiments of 0.45. LaFiette and Fantino (1988) have also reported overmatching in closed-economy multiple schedules, at least at component durations similar to those used by Elliffe and Davison.

One variable known to affect sensitivity in multiple schedules is the level of deprivation of the scheduled reinforcer. Both Herrnstein and Loveland (1974) and Charman and Davison (1983), using pigeons responding for food reinforcers on open-economy multiple VI schedules, found that sensitivity approached strict matching ($a = 1.0$) as subjects were made less food deprived. Both Elliffe and Davison's (1985) and LaFiette and Fantino's (1988) subjects were able to earn

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Table 1

Sequence of conditions in all parts of the experiment, and deprivation level for each bird, expressed as a percentage of its free-feeding body weight. Conditions 49 to 55 (Part 4) are each listed more than once, because each bird experienced a different pair of VI schedules and arranged overall reinforcer rate.

Condition	Part	Session duration	Arranged reinforcers per hour	VI schedules (in s)		Percentage of free-feeding weight		
				Red	Green	250	251	252
1	1	24 hr	60	60	60	—	93	99
2	1	24 hr	60	34	270	—	96	100
3	1	24 hr	60	270	34	—	96	101
4	1	24 hr	60	38	150	—	99	—
5	1	24 hr	60	150	38	—	99	—
6	1	24 hr	60	45	90	—	98	102
7	1	24 hr	60	90	45	—	97	101
8	1	100 comps	60	34	270	—	—	95
9	1	100 comps	60	270	34	—	—	92
10	1	100 comps	60	34	270	—	—	91
11	1	80 comps	60	270	34	—	—	88
12	1	80 comps	60	34	270	—	—	87
13	1	80 comps	60	270	34	91	90	87
14	1	80 comps	60	34	270	91	90	87
15	1	40 comps	60	270	34	85	86	81
16	1	40 comps	60	34	270	82	84	79
17	1	40 comps	60	270	34	81	84	77
18	2	50 comps	60	270	34	79	80	75
19	2	60 comps	60	270	34	82	81	76
20	2	80 comps	60	270	34	83	82	79
21	2	100 comps	60	270	34	88	84	79
22	2	110 comps	60	270	34	94	86	78
23	2	120 comps	60	270	34	98	88	81
24	2	130 comps	60	270	34	101	88	82
25	2	140 comps	60	270	34	104	91	83
26	2	150 comps	60	270	34	107	91	84
27	2	160 comps	60	270	34	105	93	85
28	2	198 comps	60	270	34	107	93	88
29	2/3	24 hr	60	270	34	106	98	96
30	3	24 hr	60	38	150	95	98	97
31	3	24 hr	60	150	38	91	100	97
32	3	24 hr	60	34	270	92	100	97
33	3	24 hr	60	60	60	91	99	96
34	3	24 hr	30	120	120	92	96	90
35	3	24 hr	30	300	76	91	96	88
36	3	24 hr	30	70	420	89	96	87
37	3	24 hr	15	840	140	89	89	79
38	3	24 hr	15	152	600	87	88	78
39	3	24 hr	15	600	152	86	86	77
40	3	24 hr	15	140	840	86	83	76
41	3	24 hr	30	70	420	88	92	86
42	3	24 hr	30	420	70	88	95	86
43	3	24 hr	30	70	420	90	95	88
44	3	24 hr	20	102	630	—	—	83
45	3	24 hr	20	630	102	—	—	82
46	3	24 hr	10	210	1,260	90	87	—
47	3	24 hr	10	1,260	210	79	82	—
48	3	24 hr	8	264	1,520	—	78	—
49	4	40 comps	60	34	270	75	81	—
			78	26	208	—	—	76
50	4	50 comps	53	38	304	74	—	—
			60	34	270	—	79	—
			127	16	128	—	—	81

Table 1
(Continued)

Condition	Part	Session duration	Arranged reinforcers per hour	VI schedules (in s)		Percentage of free-feeding weight		
				Red	Green	250	251	252
51	4	60 comps	48	42	338	77	—	—
			53	38	304	—	81	—
			101	20	160	—	—	80
52	4	70 comps	48	42	338	79	—	—
			53	38	304	—	81	—
			101	20	160	—	—	81
53	4	100 comps	37	54	434	85	—	—
			35	58	470	—	83	—
			78	26	208	—	—	81
54	4	150 comps	30	68	542	83	—	—
			28	72	580	—	82	—
			72	28	228	—	—	80
55	4	24 hr	28	72	580	84	82	—
			72	28	228	—	—	76

enough food reinforcement in their closed economies to maintain them at close to their free-feeding weights. This minimal deprivation level may go some way towards explaining the overmatching found in the closed-economy studies.

The present series of experiments set out to determine the effects of food deprivation on response allocation in closed-economy multiple schedules. Herrnstein and Loveland (1974) and Charman and Davison (1983) varied deprivation by manipulating the amount of postsession food given to each subject. Because this method violates the closed economy, two alternative techniques were employed. In Parts 1, 2, and 4, the length of time for which the multiple schedule was available each day was varied. In Parts 3 and 4, the overall reinforcer rate made available by the multiple schedule was varied. Both these manipulations changed the total number of reinforcers delivered each day, and consequently altered the deprivation level that each subject attained.

METHOD

Subjects

Three adult homing pigeons, numbered 250 to 252, served as subjects. Birds 251 and 252 had previous experience of responding on concurrent schedules, and Bird 250 had previously served in a multiple-schedule experiment. Not all birds participated in all ex-

perimental conditions. Water and grit were freely available in each bird's experimental cage.

Apparatus

Each bird lived in a cage 375 mm high, 375 mm wide, and 380 mm deep. The back, left, and right walls of the cage were made of sheet metal, and the top, floor, and front wall consisted of metal bars. Each cage contained two wooden perches, one mounted 75 mm from and parallel to the floor and front wall, and one mounted 75 mm from and parallel to the floor and right wall.

The right wall contained three translucent response keys, 20 mm in diameter and centered 114 mm apart and 223 mm above the perches. The right and center keys were dark and inoperative. The left key could be transilluminated red or green and, when lit, could be operated by pecks of a force exceeding 0.1 N. A hopper that contained wheat was located behind an aperture (45 mm by 45 mm) situated 138 mm below the center key. During reinforcer delivery, this hopper was raised and illuminated for 3 s and the keylight was extinguished.

The cages were located in a room containing the home cages of about 100 other pigeons. A good deal of activity took place in this room throughout the day. The room's ambient lighting was on between 6:00 a.m. and 7:00 p.m. each day. All experimental events were controlled and data were record-

ed by conventional solid-state and electro-mechanical equipment in another room.

Procedure

At all times, the only source of food available to each bird was wheat obtained as reinforcement for responding on multiple VI schedules. The two components of the multiple schedule alternated strictly every 150 s and were signaled by the color (red or green) of the left response key. The VI schedules arranged in each component were randomized from the first 12 terms of an arithmetic progression in which the smallest term was one 12th of the mean term. Each bird was taken from its cage to be weighed at 9:00 a.m. each day (between 12:00 a.m. and 1:00 p.m. in Conditions 1 through 7). The data (numbers of responses emitted, times spent, and reinforcers obtained in each component) were also recorded at this time.

Experimental conditions remained in force until a defined stability criterion had been met five times, not necessarily consecutively, by each bird, and the body weight of each bird appeared to be stable by inspection. The criterion required that the median relative response rate in the red component over a block of five consecutive sessions be within .05 of the median of the immediately preceding five sessions. This criterion was adhered to for Parts 1, 3, and 4, but not for Part 2, in which conditions were changed when (a) at least 10 sessions had been conducted, and (b) each bird's response allocation and body weight appeared to be stable by inspection.

The sequence of conditions in all parts of the experiment is shown in Table 1, which also shows the mean deprivation level, expressed as a percentage of free-feeding body weight attained by each bird during the last 5 days of each condition. Conditions 1 through 7 and 29 through 33 were also reported by Elliffe and Davison (1985).

Part 1 (Conditions 1 through 17) decreased session duration over four levels from 24 hr (continuous sessions) to 40 components of the multiple schedule (about 100 min). At each session duration, the distribution of reinforcers between components was varied by changing the red and green VI schedules. The arranged overall reinforcer rate was held constant at 60 reinforcers per hour. Part 2 (Conditions 18 through 29) in-

creased session duration over 12 levels from 50 components to 24 hr, while keeping the red and green VI schedules constant at VI 270 s and VI 34 s, respectively. Again, arranged overall reinforcer rate was always 60 reinforcers per hour.

Part 3 (Conditions 29 through 48) decreased arranged overall reinforcer rate over six levels between 60 and 8 reinforcers per hour, while maintaining 24-hr sessions. The distribution of reinforcers between components was varied at all overall reinforcer rates except eight reinforcers per hour. Finally, Part 4 (Conditions 49 through 55) increased session duration over seven levels from 40 components to 24 hr, while decreasing arranged overall reinforcer rate so as to keep percentage of free-feeding weight constant. The overall reinforcer rates and VI schedules for Part 4 were manipulated separately for each bird to produce a body weight close to 80% of free-feeding weight.

RESULTS

The Appendix shows the numbers of responses emitted per minute and reinforcers obtained per hour in the red and green components of the multiple schedule, together with the deprivation level attained by each bird in each condition. All data are means calculated over the last five sessions of each condition. The time base for the calculation of rates was the time spent in each component excluding the time occupied by reinforcer delivery.

Part 1

Figure 1 shows log component response-rate ratios as functions of log component reinforcer-rate ratios in each condition. The slope of the straight line represents sensitivity to reinforcement (a in Equation 1), and its intercept represents bias ($\log c$). Table 2 summarizes the generalized-matching analyses and the changes in deprivation in Part 1. The generalized matching law described the data well: Only one value of r^2 fell below .96, and no standard deviation of slope or intercept exceeded 0.13. For each bird, percentage of free-feeding weight decreased monotonically with decreasing session duration (randomization test, $p < .01$). Across birds and session durations, bias was slightly (median $\log c =$

Fig. 1. The log (base 10) of the ratio of response rates emitted in the red and green components as a function of the log of the ratio of obtained reinforcer rates. The data are means over the last 5 days of each condition in Part 1, and are plotted separately for each bird and session duration. The best fitting straight line and its equation are shown on each plot.

Table 2

Fits of the log transform of the generalized matching law and percentage of free-feeding weight (%FFW) for each bird at each session duration in Part 1. The standard deviations of slope and intercept and the proportion of variance accounted for (r^2) are shown for those fits for which more than two conditions were conducted.

Bird	a	$\log c$	$\sigma(a)$	$\sigma(\log c)$	r^2	%FFW
24 hr						
251	1.66	-0.02	0.08	0.05	.99	97
252	1.42	0.00	0.08	0.04	.99	101
100 components						
252	1.33	-0.23	0.25	0.23	.97	93
80 components						
250	0.33	-0.07	—	—	—	91
251	0.92	0.02	—	—	—	90
252	1.05	-0.04	0.07	0.07	.99	87
40 components						
250	0.07	-0.06	0.03	0.02	.86	83
251	0.65	0.00	0.13	0.12	.96	84
252	0.62	-0.06	0.05	0.05	.99	79

-0.04) but significantly (binomial test, two-tailed $p < .05$) towards the green component. Bias showed no apparent changes with session duration.

Both Birds 251 and 252 overmatched ($a > 1.0$) in 24-hr sessions at close to their free-feeding body weights. Bird 252 also overmatched in 100-component sessions at 93% of free-feeding weight, but the large standard deviation of its slope suggests that this finding may not be reliable. In 80-component sessions, Birds 251 and 252 showed sensitivity values approximating strict matching, and Bird 250 showed substantial undermatching. In 40-component sessions, all birds undermatched, with Bird 250 showing essentially no control by the component reinforcer rates. For each bird, a decreased monotonically with decreasing session duration and, therefore, with decreasing percentage of free-feeding weight (randomization test, $p < .01$).

As Table 2 shows, the changes in session duration were sufficient to manipulate deprivation in Part 1. Sensitivity decreased monotonically with decreasing session duration, and therefore with decreasing percentage of free-feeding weight, consistent with the findings of Charman and Davison (1983) and Herrnstein and Loveland (1974). However, reliable overmatching occurred only in 24-hr sessions (Conditions 1 through 7). Part 2 of the experiment set out to map the function

relating sensitivity to deprivation, session duration, or both in more detail.

Part 2

Table 3 shows session duration in components and point estimates of sensitivity (a in Equation 1) and percentage of free-feeding weight for each bird, in each condition of Part 2. The estimates of sensitivity were calculated by assuming no generalized-matching bias between the multiple-schedule components (i.e., that $\log c$ in Equation 1 equals zero). The generally small biases found in Part 1 and their lack of correlation with session duration or percentage of free-feeding weight justify this assumption.

As in Part 1, percentage of free-feeding weight increased and sensitivity increased with increasing session duration (nonparametric trend test, Kendall, 1955, $p < .01$). All birds overmatched in 24-hr sessions (Condition 29, mean deprivation level = 100% of free-feeding weight), and Birds 251 and 252 also overmatched at several shorter session durations and lower body weights (Table 3). Birds 250 and 252 produced similar sensitivity values to those obtained at comparable body weights in Part 1. Bird 251's sensitivity values were substantially higher in Part 2 than in Part 1. Across birds, sensitivity was neither systematically higher nor lower in Part 2 than in Part 1.

Table 3

Session duration in 150-s components, point estimate of sensitivity to reinforcement (a), and percentage of free-feeding weight (%FFW) for each bird in each condition of Part 2.

Condition	Session duration	Bird 250		Bird 251		Bird 252	
		a	%FFW	a	%FFW	a	%FFW
18	50	-0.04	79	0.68	80	0.46	75
19	60	0.02	82	0.74	81	0.52	76
20	80	-0.06	83	0.69	82	0.81	79
21	100	0.01	88	1.03	84	0.89	79
22	110	0.24	94	1.19	86	1.02	78
23	120	0.47	98	1.27	88	1.16	80
24	130	0.57	101	1.31	88	1.17	82
25	140	0.58	104	1.27	88	0.95	83
26	150	0.77	107	1.33	91	1.07	84
27	160	0.98	105	1.29	93	1.06	85
28	198	0.87	107	1.51	93	1.28	88
29	24 hr	1.41	106	1.82	98	1.59	96

Part 2 therefore reconfirmed the overmatching result, at least at long session durations and high percentage of free-feeding weight, reported in Part 1 and by Elliffe and Davison (1985), and reconfirmed the expected effect of percentage of free-feeding weight on sensitivity values. However, it is interesting to note that sensitivity appeared to be more monotonically and more convincingly correlated with session duration itself than with percentage of free-feeding weight. This is most evident for Bird 250, which overmatched only in 24-hr sessions (Condition 29) and not at its highest body weight (Conditions 26 and 28). The implication is that session duration may affect sensitivity directly, and not only by means of the consequential changes in food deprivation.

Part 3 was designed to vary deprivation at a constant session duration (24 hr) by manipulating the overall reinforcer rate made available by the multiple VI VI schedule. The purpose of this manipulation was to try to separate the effects of deprivation and session duration that may have been confounded in Parts 1 and 2.

Part 3

Figure 2 shows log component response-rates as functions of log component reinforcer-rate ratios in each condition. Table 4 summarizes the generalized-matching analyses and the changes in deprivation in Part 3. Mean percentage of free-feeding weight decreased monotonically for each bird with de-

creasing arranged overall reinforcer rate (nonparametric trend test, $p < .01$). That is, varying overall reinforcer rate proved to be a successful way to manipulate food deprivation.

Table 4 shows that the generalized matching law again provided a very good description of response allocation. No value of r^2 fell below .95, and no standard deviation of slope or intercept exceeded 0.14. Bias values were generally small and did not differ systematically from zero (binomial test, $p > .05$). The sensitivity value given for Bird 251 at eight reinforcers per hour (Condition 48) is a point estimate, because the distribution of reinforcers between components was not varied at this overall rate. In general, birds were allocated to Conditions 44 through 48 (20, 10, and 8 overall reinforcers per hour) so as to produce a comparably wide range of percentages of free-feeding weight for each bird. Birds 251 and 252 overmatched substantially at all overall reinforcer rates (and therefore at all deprivation levels), whereas Bird 250 overmatched only at 60 reinforcers per hour (high percentage of free-feeding weight) and approximately matched in all other conditions.

The principal difference between these results and those of Parts 1 and 2 is that sensitivity values in Part 3 remained constant with respect to deprivation level (Table 4, see also Figure 3). This supports the possibility (noted above) that some part of the changes in sensitivity in Parts 1 and 2 may have been directly

Fig. 2. The log (base 10) of the ratio of response rates emitted in the red and green components as a function of the log of the ratio of obtained reinforcer rates. The data are means over the last 5 days of each condition in Part 3, and are plotted separately for each bird and arranged overall reinforcer rate. The best fitting straight line and its equation are shown on each plot.

Table 4

Fits of the generalized matching law and percentage of free-feeding weight (%FFW) for each bird at each arranged overall reinforcer rate in Part 3. The slope shown for Bird 251 at eight reinforcers per hour is a point estimate.

Bird	Reinforcers per hour	a	$\log c$	$\sigma(a)$	$\sigma(\log c)$	r^2	%FFW
250	60	1.35	0.01	0.05	0.03	1.00	95
	30	0.84	0.02	0.10	0.06	.95	90
	15	1.07	-0.06	0.10	0.07	.98	87
	10	1.05	-0.05	—	—	—	80
251	60	1.79	0.02	0.05	0.03	1.00	99
	30	1.78	-0.08	0.06	0.04	.99	95
	15	1.55	-0.05	0.14	0.09	.98	86
	10	1.73	0.03	—	—	—	84
	8	1.68	—	—	—	—	78
252	60	1.59	-0.01	0.04	0.03	1.00	97
	30	1.57	-0.12	0.09	0.05	.99	88
	20	1.36	0.04	—	—	—	83
	15	1.72	-0.02	0.11	0.07	.99	78

related to session duration and not to the correlated changes in deprivation. Taken together, the results of Parts 1 to 3 suggest that it should be possible to increase sensitivity by increasing session duration, while decreasing overall reinforcer rate so as to hold deprivation constant. Part 4 was designed to confirm this prediction.

Part 4

Table 5 shows percentage of free-feeding weight for each bird at each session duration in Part 4. Although these levels were not as constant as had been intended, they were close to those typically arranged in conventional short-session experiments, and showed no trend with changes in session duration (nonparametric trend test, $p > .05$). Table 5 also shows point estimates of sensitivity for each bird in each condition. All birds overmatched substantially at at least some session durations and, across birds, sensitivity increased with increasing session duration despite the lack of correlated changes in percentage of free-feeding weight (nonparametric trend test, $p < .01$; see also Figures 3 and 4). It is particularly noteworthy that Bird 250 showed no change in sensitivity during Conditions 1 through 5, when percentage of free-feeding weight changed quite substantially, but large changes in sensitivity during Conditions 5 through 7, when percentage of free-feeding weight remained essentially constant.

Overall Response Rates

Figure 5 shows overall response rates, calculated by combining responses in both red and green components, as a function of overall obtained reinforcer rates, calculated similarly, and as a function of the equivalent overall VI schedule (cf. Hursh, 1984, Figure 2), for each bird at each arranged overall reinforcer rate in Part 3. Overall response rates increased with increasing overall VI schedule or decreasing overall reinforcer rate (nonparametric trend test, $p < .05$).

DISCUSSION

Overall Response Rates

Figure 5 shows that, in Part 4, overall response rate decreased with increasing overall reinforcer rate or decreasing mean VI interval. This apparently surprising result is consistent with previous results from closed-economy experiments in which the overall reinforcer rate provided by a single VI schedule or a concurrent VI VI schedule was varied (e.g., Hursh, 1978; Hursh & Natelson, 1981; Lucas, 1981). Unlike equivalent open-economy procedures, response rate and reinforcer rate were inversely related in all these experiments.

As shown by, for example, Hursh (1980, 1984), a difference in the direction of the relation between response and reinforcer rates in closed and open economies is consistent

Fig. 3. Sensitivity values (a in Equation 1) as a function of deprivation, expressed as percentage of free-feeding weight, for each bird and the mean of all birds in Parts 1 (filled circles), 2 (open circles), 3 (filled squares), and 4 (open squares). For Part 4, the points are joined in order of increasing session duration. Each point represents the mean of the last 5 days of each condition or group of conditions arranging the same session duration and overall reinforcer rate.

with an interpretation in terms of demand elasticity. In a closed economy, demand for the reinforcer is inelastic, because no alternative source of the reinforcer is available. Consumption is therefore defended against increases in price (increasing VI interval or decreasing reinforcer rate). This can only be done by increasing response rate. In an open economy, demand is elastic because an alternative source of the reinforcer (postsession

feeding) is available. Consumption is therefore not defended against increases in price, so that response and reinforcer rate are directly related. The present results extend this finding to overall responding in multiple VI schedules.

Sensitivity

Figures 3 and 4 show sensitivity values as functions of session duration and deprivation level respectively, for each bird in each part of the experiment, together with their means. Each individual bird and the mean for the group show similar effects.

First, overmatching generally occurred in 24-hr sessions, irrespective of deprivation. The exception is Bird 250, which matched at moderate to high deprivation in Part 3, although it did show its greatest sensitivity ($a = 1.54$) at high deprivation (84% of free-feeding weight) in 24-hr sessions during Condition 55. Second, undermatching occurred at high deprivation with moderately high reinforcer rates in short sessions (e.g., Conditions 15 through 18, 49 and 50). These conditions, which are all those of about 2 hr or less in duration, produced a mean sensitivity value across birds of 0.48 (median 0.47), which compares very well with McSweeney et al.'s (1986) median value for conventional multiple-schedule experiments of 0.45. The conditions described are similar to those typically used in conventional multiple schedules, with the exception of the closed economy for food reinforcement. Third, sensitivity could be progressively increased from undermatching to overmatching by increasing session duration, either at a constant arranged overall reinforcer rate with consequent decreasing deprivation (Parts 1 and 2), or at a constant deprivation level with the necessary decreases in arranged overall reinforcer rate (Part 4). However, sensitivity could not be decreased from substantial overmatching by increasing deprivation via decreasing overall reinforcer rate in 24-hr sessions (Part 3).

These findings differ from those of Charman and Davison (1983) and Herrnstein and Loveland (1974) in two major respects. First, the present experiment produced changes in sensitivity when deprivation was varied by manipulating session duration, but not when deprivation was varied by manipulating reinforcer rate. Second, the limit to increased

Table 5

Session duration in 150-s components, point estimate of sensitivity to reinforcement (a), and percentage of free-feeding weight (%FFW) for each bird in each condition of Part 5.

Condition	Session duration	Bird 250		Bird 251		Bird 252	
		a	%FFW	a	%FFW	a	%FFW
49	40	0.47	75	0.45	81	0.85	76
50	50	0.32	74	0.47	79	0.75	81
51	60	0.29	77	0.45	81	0.96	80
52	70	0.47	79	0.39	81	0.91	81
53	100	0.43	85	1.00	83	1.20	81
54	150	0.93	83	1.13	82	1.33	80
55	24 hr	1.54	84	1.44	82	1.53	76

sensitivity in the present experiment was over-matching, not strict matching as was found in the conventional studies. These findings can be examined in the light of two influential models of multiple-schedule performance suggested by Herrnstein (1970) and McLean and White (1983). Both models emphasize the importance of extraneous reinforcement, or reinforcers available in the experimental environment but not arranged by the experimenter, in explaining deprivation effects.

Multiple-Schedule Models

Herrnstein (1970) proposed the following equation for response allocation between multiple-schedule components:

$$\frac{B_1}{B_2} = \left(\frac{R_1}{R_2} \right) \frac{R_2 + mR_1 + R_e}{R_1 + mR_2 + R_e}, \quad (2)$$

where m is a parameter varying between 0 and 1 which represents the degree of interaction between components, and R_e measures the rate at which extraneous reinforcers are obtained. The other terms in Equation 2 are as defined for the generalized matching law. As long as m is less than 1, Equation 2 predicts that the distribution of responses between components will be less extreme than the distribution of reinforcers, which is undermatching. However, as deprivation becomes minimal, the value of extraneous reinforcement R_e should increase relative to that of the food reinforcers R_1 and R_2 . At the limit, as the relative value of extraneous reinforcers approaches infinity, Equation 2 approaches strict matching.

McLean and White (1983) proposed the following equation:

$$\frac{B_1}{B_2} = \left(\frac{R_1}{R_2} \right)^a \frac{R_2^a + bR_{e2}^a}{R_1^a + bR_{e1}^a}, \quad (3)$$

where R_{e1} and R_{e2} denote extraneous-reinforcer rates obtained within each component. McLean and White's approach differs from Herrnstein's (1970) in that responding within a component is assumed to be governed by a concurrent choice between the scheduled and extraneous reinforcer rates available in that component alone, and is independent of reinforcer rates in the alternated component. McLean and White called this the assumption of successive independence. They included sensitivity and bias parameters (a and b in Equation 3) to reflect the body of findings that generalized, rather than strict, matching governs concurrent choice (e.g., Baum, 1979; Myers & Myers, 1977; Wearden & Burgess, 1982). As with Herrnstein's equation, Equation 3 predicts that multiple-schedule sensitivity will increase with decreasing deprivation.

This interpretation may be used to explain at least the directional changes in sensitivity seen in the present results. In Parts 1 and 2, sensitivity increased with decreasing deprivation (and therefore increasing value of R_e in Equation 2, or R_{e1} and R_{e2} in Equation 3) as predicted. In Part 3, sensitivity did not change when deprivation was manipulated via overall reinforcer rate. This appears at first to be inconsistent with an interpretation in terms of R_e , but recall that the approach predicts sensitivity changes only when R_e changes relative to R_1 and R_2 . When deprivation is manipulated by changing R_1 and R_2 , the prediction no longer applies. That is, it is at least possible that decreasing R_1 and R_2 in

Fig. 4. Sensitivity values (a in Equation 1) as a function of the number of multiple-schedule components per session, for each bird and the mean of all birds in Parts 1 (filled circles), 2 (open circles), 3 (filled squares), and 4 (open squares). Each point represents the mean of the last 5 days of each condition or group of conditions arranging the same session duration and overall reinforcer rate.

Part 3 produced equiproportional decreases in R_c , so as to predict no net change in sensitivity. In any case, the constant sensitivity values found cannot be used to disconfirm either model.

Dealing with the results of Part 4 requires the introduction of an additional concept, the experimental economy for extraneous reinforcement. When sessions run continuously, the total daily consumption of extraneous reinforcement must be obtained within the session, and is therefore dependent on be-

Fig. 5. Overall response rate as a function of mean VI schedule (upper graph) and obtained overall reinforcer rate (lower graph), for each bird in Part 3. Each point represents the mean of the last 5 days of each condition arranging the same overall reinforcer rate.

havior emitted during the session. This is a closed economy (Hursh, 1980, 1984). Decreasing session duration from 24 hr can be construed as arranging an alternative source of extraneous reinforcement, outside the experimental session, whose availability is independent of behavior during the session. This can be seen as progressively opening the economy for R_c . Opening the economy for a reinforcer should both reduce the intensity and increase the elasticity of demand for the reinforcer during the session (e.g., Hursh, 1980). This suggests that the obtained rate of extraneous reinforcement will decrease with decreasing session duration. As long as deprivation does not change, Equations 2 and 3 therefore predict that sensitivity will also decrease, in a manner exactly analogous to the interpretation of deprivation changes.

In Part 4, then, sensitivity should have increased with increasing session duration both because the economy for R_c became more closed and because the food reinforcer rates

(R_1 and R_2) were decreased in order to maintain constant deprivation. It is worth noting that both these effects would have influenced the results of Parts 1 and 2. There, as session duration was increased to 24 hr, not only did deprivation decrease but the economy for R_c closed. Also, the obtained reinforcer rates decreased somewhat, as might be expected with decreased deprivation (see the Appendix). All three changes should have decreased R_1 and R_2 relative to R_c , and therefore go some way towards explaining the large increases in sensitivity observed (Figures 3 and 4). Of course, no changes in the economy for R_c could be expected in Part 3, because session duration was always 24 hr. Sensitivity did not change, as shown in Figures 3 and 4.

The second major difference between the present results and those of Charman and Davison (1983) and Herrnstein and Loveland (1974) is that overmatching, rather than strict matching, was observed at low deprivation. As shown above, Herrnstein's (1970) equation predicts that strict matching will be the upper limit to sensitivity as deprivation decreases and R_c increases. Here, however, consistent and substantial overmatching was observed whenever deprivation was minimal and whenever session duration was 24 hr. That is, Herrnstein's approach correctly predicts the directional changes in sensitivity seen here, but not the absolute level of sensitivity. Other models of multiple-schedule performance (e.g., Williams, 1983; Williams & Wixted, 1986) similarly prohibit overmatching. Moreover, they do not appear to predict any effect of deprivation.

However, McLean and White's (1983) model can accommodate overmatching in two ways. First, the within-component concurrent-choice sensitivity parameter a may be greater than 1.0 so that, when R_{c1} and R_{c2} are large, Equation 3 reduces to the generalized matching law (Equation 1) with no bias and a greater than 1.0. This explanation is unlikely, because overmatching is rare in conventional concurrent schedules, and because concurrent choice between food reinforcers in closed economies does not appear to differ from that in open economies (e.g., Baum, 1972; Graft, Lea, & Whitworth, 1977; Hursh, 1978). There seems to be no reason to expect choice between food and extraneous reinforcers in a closed economy to overmatch.

Fig. 6. Data from Bird 252, Part 1. The solid line is the best least squares fit. The three dotted lines represent biased strict matching, with hypothetical bias values chosen to show how overmatching can result if bias is correlated with the reinforcer-rate ratio.

The second way in which overmatching can arise from Equation 3 is more complicated. McLean and White (1983) showed, in a multiple concurrent schedule, that constant and unequal component extraneous-reinforcer rates produced a bias, in generalized-matching terms, to the component with the lower extraneous reinforcer rate. Suppose, however, that the ratio of component extraneous-reinforcer rates varies inversely with the ratio of component food-reinforcer rates. That is, if R_1 is greater than R_2 , then R_{c2} is greater than R_{c1} . In such a case, the bias produced by the unequal extraneous-reinforcer rates would be correlated with the food-reinforcer rate ratio. This correlated bias could produce apparent overmatching, whatever the underlying sensitivity to the food-reinforcer rate ratio. As an example, Figure 6 shows how this mechanism could have produced overmatching for Bird 252's data in Part 1.

This interpretation requires a systematic inverse relationship between scheduled and extraneous reinforcer rates in each component. Such a relationship is plausible: Increases in

(say) R_1 should produce corresponding increases in B_1 . By competition between two concurrent responses, B_{e1} (responding for R_{e1}) should then decrease. Given Pear's (1975) suggestion that R_e is available on ratio-like schedules and therefore that the slope of its feedback function is positive, R_{e1} should decrease. In fact, this is the mechanism McLean and White (1983) offered for behavioral contrast (Reynolds, 1961).

Unfortunately, Equation 3 cannot be fitted directly to these, or any, multiple-schedule data, because the values of R_{e1} and R_{e2} can be expected to be different for every pair of food-reinforcer rates (i.e., for every experimental condition). The consequence is that the number of free parameters in fitting Equation 3 is always double the number of experimental conditions, plus the sensitivity and bias parameters a and b . Equation 3 is therefore not directly testable.

Economic Interpretation

The most apparent novel feature of the experimental procedure used here was the closed economy for food reinforcement. As discussed earlier, this feature can be used to interpret the observed inverse relation between overall response and reinforcer rates (Figure 5). It may also be possible to interpret the observed effects on sensitivity in economic terms. One such interpretation, suggested by a reviewer of this paper, considers session duration as being analogous to income. When income is increased in a closed economy, consumption shifts to the more preferred commodity (e.g., Hursh & Bauman, 1987). Here, the preferred commodity is assumed to be reinforcement from the multiple-schedule component providing the higher reinforcer rate.

In the present experiments, the only way to defend body weight in short sessions (low income) is to obtain reinforcers from both multiple-schedule components. As session duration increases to 24 hr, it becomes possible to confine most consumption, and therefore most responding, to the higher reinforcer-rate component, and still defend body weight. This predicts an increasing differential between component response rates at long session durations.

The income interpretation fails on two counts. First, it rests on differential changes

in consumption (obtained reinforcer rates) in the two components, and predicts that responding will change with these changes in consumption. However, the generalized matching law itself involves obtained reinforcer rates. That is, changes in sensitivity imply changes in the relation between responding and obtained reinforcer rates. The economic interpretation does not predict such changes. Second, there is in any case no evidence that consumption of food in the two components changed differentially with session duration in the required manner. In Part 2, for example, there was no evident trend in the ratio of obtained component reinforcer rates (see the Appendix) with increasing session duration (nonparametric trend test, $p > .05$). The economic interpretation would require the ratio of component reinforcer rates to become more extreme at long session durations.

The interpretation of these results in terms of extraneous reinforcement seems to be more promising than the income-based account. However, neither Herrnstein's (1970) nor McLean and White's (1983) equations can provide a fully satisfactory quantitative expression of the effects of R_e . Herrnstein's model fails because it prohibits overmatching, and McLean and White's model is not directly testable. The best approach may be to produce a constrained version of Equation 3 by limiting the ways in which R_{e1} and R_{e2} are permitted to change. For example, the ratio of extraneous-reinforcer rates (R_{e1}/R_{e2}) could be assumed to be some simple inverse function of the food-reinforcer ratio (R_1/R_2). However, such elaborations of McLean and White's model go beyond the scope of the present discussion.

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APPENDIX

Mean numbers of responses emitted per minute and reinforcers obtained per hour in the red and green components of the multiple schedule, and mean deprivation level attained, by each bird in the last five sessions of each condition. Deprivation level is shown as a percentage of the bird's free-feeding body weight.

Bird	Condition	Responses per minute		Reinforcers per hour		Percentage of free-feeding weight
		Red	Green	Red	Green	
250	13	26.47	62.91	13.85	117.69	91
	14	64.15	37.19	117.01	13.74	91
	15	75.46	108.19	13.82	118.40	85
	16	73.02	72.26	118.13	13.91	82
	17	48.55	60.38	13.75	117.63	81
	18	54.43	49.76	13.74	116.92	79
	19	43.37	45.52	13.59	114.76	82
	20	45.65	39.85	13.79	116.30	83
	21	36.90	37.85	13.48	116.83	88
	22	22.17	37.06	13.30	115.25	94
	23	13.91	39.14	12.71	113.99	98
	24	8.63	29.86	12.28	108.86	101
	25	7.43	27.04	11.85	108.30	104
	26	3.95	20.75	10.60	91.48	107
	27	3.05	22.25	10.18	76.86	105
	28	2.96	14.87	9.53	60.40	107
	29	0.56	8.13	3.41	22.66	106
	30	5.37	0.72	12.41	2.86	95
	31	1.08	6.33	4.32	18.17	91
	32	5.50	0.36	16.55	2.24	92
	33	3.84	3.56	9.51	8.98	91
	34	8.76	9.42	10.41	10.48	92
	35	5.12	17.43	2.87	12.05	91
	36	13.84	3.48	12.51	2.43	89
	37	2.37	20.23	2.10	10.69	89
	38	25.28	6.74	10.40	2.51	87
	39	7.19	25.56	2.64	10.24	86
	40	22.36	3.73	11.99	2.04	86
	41	12.33	4.10	11.46	2.06	88
	42	4.18	16.34	2.17	12.79	88
	43	14.17	2.32	14.67	3.37	90
	46	30.87	6.18	7.96	1.52	80
	47	4.82	25.48	2.13	9.33	79
	49	104.09	39.37	101.72	12.61	75
	50	89.49	42.88	93.93	9.24	74
	51	83.64	45.64	84.38	10.26	77
	52	83.51	31.68	70.47	8.92	79
	53	71.01	27.70	41.54	4.63	85
	54	73.73	21.06	22.80	5.93	83
	55	10.15	1.24	15.74	4.02	84
251	1	4.86	6.52	12.27	13.02	93
	2	7.83	0.43	23.84	3.83	96
	3	0.43	6.53	3.90	23.91	96
	4	7.76	0.67	22.77	5.89	99
	5	0.56	6.75	5.98	20.38	99
	6	5.67	1.73	16.68	7.96	98
	7	1.84	6.65	7.93	17.39	97
	13	15.41	105.62	13.86	118.00	90
	14	97.42	13.02	115.60	13.74	90
	15	20.09	112.00	13.82	117.57	86
	16	105.50	26.11	116.96	13.65	84
	17	33.00	98.40	14.03	117.42	84
	18	24.58	106.10	13.52	117.73	80
	19	19.34	94.48	13.59	116.92	81
	20	21.28	93.11	13.78	116.86	82
	21	11.19	103.17	13.38	116.43	84

APPENDIX

(Continued)

Bird	Condition	Responses per minute		Reinforcers per hour		Percentage of free-feeding weight
		Red	Green	Red	Green	
	22	6.82	91.65	13.09	116.71	86
	23	5.25	83.88	13.07	116.11	88
	24	4.71	83.49	12.78	115.62	88
	25	4.94	79.63	12.85	115.45	88
	26	3.65	65.66	12.18	107.69	91
	27	3.43	54.13	11.99	102.11	93
	28	2.12	52.31	11.05	92.81	93
	29	0.40	10.73	4.19	25.76	98
	30	6.97	0.80	19.38	5.80	98
	31	0.73	7.84	5.58	21.50	100
	32	7.93	0.39	20.86	3.86	100
	33	3.09	2.49	12.37	12.52	99
	34	2.35	3.26	10.97	11.32	96
	35	1.09	10.85	5.01	17.26	96
	36	10.18	1.15	17.98	4.03	96
	37	1.45	15.76	2.82	14.10	89
	38	15.97	2.54	13.00	3.00	88
	39	1.10	9.04	3.62	11.14	86
	40	11.15	0.81	12.97	2.78	83
	41	12.22	0.74	22.39	4.74	92
	42	0.51	9.16	4.15	18.74	95
	43	11.34	0.80	21.23	4.55	95
	46	12.95	0.84	9.07	1.92	87
	47	0.93	13.57	1.88	9.12	82
	48	16.69	1.29	7.63	1.66	78
	49	67.83	26.14	110.90	13.10	81
	50	56.54	20.88	110.72	13.35	79
	51	54.71	20.66	99.02	11.46	81
	52	57.69	25.40	97.09	11.69	81
	53	48.44	5.74	62.66	7.40	83
	54	45.12	3.97	50.49	5.87	82
	55	8.60	0.56	22.07	3.31	82
252	1	2.40	2.78	10.91	11.22	99
	2	6.23	0.55	21.02	3.64	100
	3	0.59	7.30	3.58	22.95	101
	6	5.71	1.36	16.96	7.36	102
	7	2.48	8.09	8.56	17.06	101
	8	66.03	13.56	96.75	12.40	95
	9	2.57	74.82	11.74	100.12	92
	10	97.86	5.43	107.67	12.77	91
	11	8.44	115.60	12.70	109.09	88
	12	99.45	10.28	109.17	13.04	87
	13	13.06	95.86	13.59	108.50	87
	14	81.53	10.58	108.31	12.93	87
	15	17.90	84.99	13.56	107.90	81
	16	74.38	24.05	107.91	13.65	79
	17	24.08	87.84	13.50	107.68	77
	18	36.26	92.34	13.97	108.22	75
	19	21.27	62.18	13.23	105.18	76
	20	12.66	68.48	13.25	106.32	79
	21	9.27	60.79	12.71	104.75	79
	22	10.36	90.27	12.81	106.67	78
	23	8.77	103.24	12.81	107.46	80
	24	6.29	77.45	12.37	105.36	82
	25	11.32	78.56	12.62	97.39	83
	26	8.90	82.06	11.89	95.10	84
	27	9.64	90.76	11.99	100.18	85
	28	5.33	83.85	11.22	96.21	88
	29	0.71	14.53	4.42	29.74	96

APPENDIX

(Continued)

Bird	Condition	Responses per minute		Reinforcers per hour		Percentage of free-feeding weight
		Red	Green	Red	Green	
	30	10.70	1.31	22.24	6.58	97
	31	0.92	8.09	6.17	23.49	97
	32	8.19	0.61	22.68	4.05	97
	33	2.40	3.05	11.86	12.71	96
	34	6.47	8.88	11.76	12.11	90
	35	2.68	30.18	5.68	21.06	88
	36	26.63	1.68	22.72	4.49	87
	37	1.79	28.96	2.65	13.65	79
	38	29.15	2.42	13.40	3.69	78
	39	2.62	28.09	3.59	12.70	77
	40	22.59	1.80	13.93	2.63	76
	41	8.10	1.15	22.83	4.45	86
	42	1.84	29.24	4.52	23.43	86
	43	11.92	1.33	23.05	4.45	88
	44	25.35	1.87	17.29	2.70	83
	45	2.75	35.16	2.50	17.41	82
	49	74.16	12.64	130.90	16.25	76
	50	64.26	13.62	210.87	26.43	81
	51	79.09	11.62	172.72	23.52	80
	52	83.51	13.87	172.72	23.99	81
	53	87.41	6.38	132.32	15.00	81
	54	78.78	5.34	123.43	16.28	80
	55	21.17	1.18	29.56	4.50	76