

NONSTABLE CONCURRENT CHOICE IN PIGEONS

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Six pigeons were trained on concurrent variable-interval schedules in which the arranged reinforcer ratios changed from session to session according to a 31-step pseudorandom binary sequence. This procedure allows a quantitative analysis of the degree to which performance in an experimental session is affected by conditions in previous sessions. Two experiments were carried out. In each, the size of the reinforcer ratios arranged between the two concurrent schedules was varied between 31-step conditions. In Experiment 1, the concurrent schedules were arranged independently, and in Experiment 2 they were arranged nonindependently. An extended form of the generalized matching law described the relative contribution of past and present events to present-session behavior. Total performance in sessions was mostly determined by the reinforcer ratio in that session and partially by reinforcers that had been obtained in previous sessions. However, the initial exposure to the random sequence produced a lower sensitivity to current-session reinforcers but no difference in overall sensitivity to reinforcement. There was no evidence that the size of the reinforcer ratios available on the concurrent schedules affected either overall sensitivity to reinforcement or the sensitivity to reinforcement in the current session. There was also no evidence of any different performance between independent and nonindependent scheduling. Because of these invariances, this experiment validates the use of the pseudorandom sequence for the fast determination of sensitivity to reinforcement.

Key words: concurrent schedules, choice, acquisition, generalized matching, key peck, pigeons

In general, research on concurrent choice has concentrated on steady-state relations between the relative allocation of behavior and independent variables that are associated with reinforcement or aspects of responding. The development of quantitative models describing stable-state choice has been successful, and is exemplified by the generalized matching law (see Davison & McCarthy, 1988, for a review), which provides a description of the relation between behavior-output ratios and reinforcer-input ratios when two variable-interval (VI) schedules are concurrently available. This relation can be written as

$$\log \frac{B_1}{B_2} = a \log \frac{R_1}{R_2} + \log c. \quad (1)$$

Equation 1 is the commonly used logarithmic form of the generalized matching law. The

parameter a is termed sensitivity to reinforcement, and measures the sensitivity with which the independent variable controls the allocation of responding. $\log c$ is called response bias, and is a constant proportional preference, independent of the reinforcer ratio, toward one of the alternatives. The logarithmic form of the generalized matching law is the most convenient, because fitting a least squares regression line to the dependent variable as a function of the independent variable yields a straight-line function with slope a and intercept $\log c$.

The emphasis on stable-state research designs over past decades has largely been at the expense of studies of the behavior that occurs in transitional situations in which reinforcer ratios, or other parameters, vary in some way. The aim of the present experiments was to clarify the effects of changes in reinforcement parameters that occur between sessions rather than between blocks of sessions. We ask, as did Hunter and Davison (1985), how the reinforcement conditions in previous sessions affect current behavior. We also ask whether these session-to-session effects are affected by the size of the reinforcer-ratio changes between sessions.

Hunter and Davison (1985) trained pigeons on concurrent VI VI schedules in

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which the independently arranged reinforcer ratio on the two keys could change, each session, between two reciprocal values (4:1 and 1:4). The changes were arranged according to a 31-step pseudorandom binary sequence (PRBS). This sequence is a random sequence in the sense that there are no sequential dependencies, even though the sequence is deterministically generated and is short in length (Poortvliet, 1962). The aim of Hunter and Davison's experiment was to determine the dynamics of concurrent VI performance through an analysis of output (behavior ratios) as a function of both present and past inputs (reinforcer ratios). They found that both the reinforcer ratio in the present session and those in previous sessions did affect behavior. Their analyses suggested that three or four sessions were required, following a step change in the reinforcer ratio, to bring the log response ratio to within 95% of its final, steady-state, value. Beyond this point, no significant effect of sessional reinforcer ratios could be demonstrated. These findings were similar to those reported by Davison and Hunter (1979), who investigated performance in concurrent VI VI schedules that changed every six sessions, with the reinforcer ratio being progressively increased and then decreased. They found that the response-rate ratios following a change in the reinforcer-rate ratio had reached their steady-state asymptotic level before the sixth session after the change.

Davison and McCarthy (1988) showed that Equation 2, a version of Equation 1 extended to include previous sessions' reinforcer ratios, could account accurately for present-session performance when reinforcer ratios were frequently changing.

$$\log \frac{B_{1n}}{B_{2n}} = a_0 \log \frac{R_{1n}}{R_{2n}} + a_1 \log \frac{R_{1(n-1)}}{R_{2(n-1)}} + \dots + a_9 \log \frac{R_{1(n-9)}}{R_{2(n-9)}} + \log c, \quad (2)$$

where the variables are the same as in Equation 1, and n denotes the current session, $n - 1$ is the previous session, and so on. Such an equation is fit to all response ratios in a sequence of changing reinforcer ratios, using, for instance, the current and previous nine sessions' reinforcer ratios. Naturally, re-

inforcer ratios in sessions prior to the start of the varying sequence will also need to be used. It should be evident that the results of such a fit naturally predict the stable-state performance following a sustained step change in reinforcer ratios, as in the standard stable-state procedure. Under stable-state conditions, all contributing reinforcer ratios in Equation 2 are approximately the same, and the summation of all the sensitivity values in the equation provides an estimate of the stable-state sensitivity. Hunter and Davison found that stable-state response-allocation sensitivity ranged across subjects from 0.33 to 0.71 ($M = 0.53$). These values are somewhat lower than those usually obtained from stable-state concurrent VI VI experiments, for which the typical ranges are 0.8 to 1.0 (Baum, 1979; Wearden & Burgess, 1982). The reason for their obtaining lower overall a values than those from stable-state experimentation is unclear. It may be that random and frequent session-to-session changes in the reinforcer ratio do, in fact, decrease the overall sensitivity to reinforcement. Some evidence supporting this explanation was provided by Shettleworth and Plowright (1992). They compared foraging performances in environments that changed at an unpredictable time every five sessions with ones that changed every session and ones that could change every trial. They concluded that what might be called the pigeons' *memory window* for prey density is a function of the frequency of alteration of the environment. In particular, after training in a random environment, performance was unaffected by the reinforcer parameters in the previous trial. This is a reasonable strategy, because the previous trial provided no information about future environment.

Davison and McCarthy (1988) reported a reanalysis of data from Hunter and Davison's (1985) experiment. Using Equation 2 rather than Hunter and Davison's nonlinear systems analysis, they confirmed Hunter and Davison's conclusion that statistically significant effects of previous reinforcer ratios had disappeared after three sessions (sensitivity to reinforcement values were significantly positive up to a lag of three sessions according to a binomial test). They found, on average, a sensitivity to reinforcement in the present session of 0.3, in the previous session of 0.2, which then fell to 0.075 and 0.04 in the next

two sessions back. However, they noticed that the cumulated average sensitivity values increased from 0.62 when the previous three sessions' reinforcers were used, to 0.70 when the last 10 sessions were taken into account. They suggested that Hunter and Davison may have missed some longer term process that may have been affecting behavior.

To summarize, research has suggested that the effect of previous and current sessional reinforcer ratios in concurrent VI VI schedules on choice can be quantitatively predicted. The period over which prior effects may be reliably seen appears to be between four and six 1-hr experimental sessions for pigeons (Davison & Hunter, 1979; Hunter & Davison, 1985). This is substantially less than the 15 to 30 sessions conventionally used for stabilizing behavior on concurrent schedules. However, the criteria used to define stability are arbitrary, and it often takes at least 10 sessions, or more, to meet some of these criteria (Davison & Hunter).

Plowright and Shettleworth (1990) showed that the variability in an organism's environment can affect the speed at which behavior changes following environmental changes. They trained pigeons on concurrent random-ratio schedules in which the alternative with the higher probability of reinforcement changed randomly from session to session. In three different conditions, the values of the reinforcer probability pairs were .9 and .1, .9 and .5, and .5 and .1. They reported a difference in the rate of acquisition of preference as a function of the probability of reinforcement, the fastest rate being produced by the .9-.1 probability pair. In related research, Bailey and Mazur (1990), Mazur and Ratti (1991), and Mazur (1992) all measured the acquisition of preference for the higher probability of reinforcement using various choice procedures. Bailey and Mazur used a discrete-trials choice procedure to investigate how the difference between reinforcement probabilities influences the rate at which asymptotic performance was reached. Like Plowright and Shettleworth (1990), they found that performance reached an asymptotic level more quickly when the ratio of the two reinforcement probabilities was larger. Mazur and Ratti used the same general procedure and design as that used by Bailey and Mazur, but

investigated free-operant choice. They reported similar results.

Mazur (1992) extended these findings. Experiment 1 investigated the effects of overall reinforcer rate on concurrent choice between reinforcement alternatives with a constant difference between the probabilities of reinforcers on the two alternatives. Mazur reported that preference acquisition was faster for a 5:1 reinforcer ratio than for a 2:1 reinforcer ratio. Experiment 2 was similar to Experiment 1 except that concurrent VI schedules assigned reinforcers instead of concurrent variable-ratio (VR) schedules. Reinforcer ratios of 3:2, 7:3, and 9:1 were used with a constant overall reinforcer rate. For concurrent VI VI schedules, Mazur concluded that the rate of approach to asymptotic performance was independent of the reinforcer ratio.

To summarize, research shows that choice behavior adjusts to changing environments, and this adjustment may occur more rapidly when organisms are exposed to environments that frequently change over sessions. At the limit, choice behavior may come to be controlled largely by reinforcer deliveries in the current session and be largely independent of those in previous sessions. Indeed, other research (e.g., Mark & Gallistel, 1994) has shown that preference can change rapidly even within a few reinforcer deliveries in a session.

The present experiments were systematic replications and extensions of the experiment reported by Hunter and Davison (1985). The experiments also constituted systematic replications, but with a different procedure, of Mazur's (1992) Experiment 2. Like these previous experiments, the present experiments investigated the degree to which reinforcers delivered in previous sessions affected present-session choice performance, and hence the speed at which subjects' choice behavior changed in such conditions. Both experiments used Hunter and Davison's (1985) pseudorandom sequence approach, and varied the reinforcer ratio between the alternatives across conditions. This design allows us to determine whether Hunter and Davison's results have generality over differing reinforcer ratios, and hence to determine the generality of Mazur's finding that the size of reinforcer ratios does not affect the speed

of transition on concurrent VI VI schedules. The present two experiments differed in terms of the arrangement of the concurrent schedules: In Experiment 1, the schedules were arranged independently. Because of a concern that response ratios were affecting reinforcer ratios, Experiment 2 used nonindependent concurrent schedules.

EXPERIMENT 1

METHOD

Subjects

Six adult homing pigeons, numbered 111 to 116, were maintained at $85\% \pm 15$ g of their free-feeding body weights by giving postsession feeding as necessary. Water and grit were freely available in their home cages. All subjects had prior experience on concurrent schedule procedures. Bird 111 died following Experiment 1 and was replaced with a bird that was experienced on concurrent schedule procedures.

Apparatus

A standard experimental chamber, 310 mm wide, 340 mm deep, and 340 mm high, was used. It contained three keys, each 20 mm in diameter, and centered 115 mm apart and 250 mm above the grid floor. The center key was dark and inoperable throughout. The side keys were illuminated white. An effective response on either key required a force of approximately 0.1 N, and responses to dark keys were ineffective and not recorded. Reinforcement consisted of 3-s access to wheat through an aperture (50 mm by 50 mm) situated 100 mm above the grid floor and beneath the center key. During reinforcement, the feeder was illuminated and the side keys were darkened. A ceiling-mounted house-light, which provided general illumination, was also darkened during reinforcement. A ventilation fan provided both air circulation and masking noise. An IBM PC-compatible computer situated remote from the experimental chamber ran MED-PC® programs that controlled experimental events and recorded the results.

Procedure

In each condition, two exponential VI schedules were arranged on the side keys by

querying probability gates, set at appropriate values, every 1 s under the constraint, throughout, that the overall arranged rate of reinforcers was four per minute. A 3-s changeover delay (Herrnstein, 1961) prevented responses from producing a reinforcer on a given alternative until 3 s had elapsed since the first response on that alternative after changing over from the other alternative.

Experimental sessions lasted either 45 min or until 40 reinforcers had been obtained, whichever came first. Sessions were run once a day, 7 days a week in Experiment 1 and 6 days a week in Experiment 2. Each session started and finished in blackout. At the end of each session the number of responses on both the left and right keys, the time spent responding on each key, the reinforcers obtained on both keys, and the number of changeovers between the two alternatives were recorded. The time spent responding on each key was measured from the first response on that key until the first response on the other key.

In Experiment 1, following the procedure of Hunter and Davison (1985), the concurrent schedules were arranged independently. Thus, if a reinforcer was arranged for one schedule, the other schedule continued timing and could set up further reinforcers. Experiment 1 consisted of three conditions. For the first 10 sessions of each condition, the probability of reinforcement for each VI schedule was .0167 per second (concurrent VI 60 s VI 60 s). In the following 31 sessions of each condition, the arranged reinforcer ratio was switched between two values according to a 31-step sequence, keeping the overall probability of reinforcement per second constant. The size of the reinforcer ratios available on the concurrent schedules varied across conditions: In Condition 1, the arranged reinforcer ratio was either 4:1 (VI 37.4 s and VI 150 s) or 1:4; in Condition 2 it was 8:1 (VI 269 s and VI 33.7 s) or 1:8; and in Condition 3 it was 2:1 (VI 89.8 s and VI 44.9 s) or 1:2. Which of these pairs was in operation in a session was determined by the random sequence.

RESULTS

The data used in the following analyses were the number of responses emitted on the left and right keys, the time spent on the left

and right keys, and the number of reinforcers obtained on the left and right keys in each session. In the analyses, the independent variable (input) was the logarithm (base 10) of the ratio of the obtained reinforcer frequencies in each session, including the 10 equal reinforcer-frequency sessions that preceded the random sequence. The dependent variable (output) was the logarithm of the ratio of the responses (response analysis), and the logarithm of the ratio of the time spent responding, on the left and right alternatives (time analysis) in each session of the random sequence.

To enable log-ratio values to be determined when choice was exclusive or when reinforcers occurred exclusively on one alternative, values of 2.99 and -2.99 were allocated for exclusive left choices or reinforcer allocations and exclusive right choices or reinforcer allocations, respectively. This was done because a session with an infinite reinforcer ratio (and most instances were infinite reinforcer ratios rather than response ratios) could not simply be dropped from the analysis without completely compromising it. But in terms of the model, the reinforcer ratio was extreme in such conditions and would clearly have a large effect. We simply used the ratio 999:1 because it was both large and non-infinite. Infinite reinforcer ratios occurred in eight sessions for Bird 112 in Sequence 2 (8:1 reinforcer ratio) and very infrequently otherwise. This procedure, then, could have led to some biases in parameter estimates for Bird 112.

The first question that must be answered before considering an input-output analysis is the extent to which the system is closed (i.e., the input depends on the output) or open (i.e., the input is independent of the output). If the output (behavior) alters the dynamics of the input (i.e., if there is a discrepancy between the arranged and obtained reinforcer ratios), then the system must be at least partially closed. If the system is closed, then the intended independent variable (the log reinforcer ratio obtained) is not, in fact, independent, and regression analyses of the results may not provide valid slope and intercept values. For both the 2:1 and 8:1 reinforcer ratios, the obtained reinforcer ratios were significantly higher than the arranged reinforcer ratios (sign test across subjects, p

$< .05$), although this difference was not significant for the 4:1 reinforcer ratio. Thus, it was usually, but not always, the case that the independent-scheduling procedure allowed response allocation to drive reinforcer ratios. The system, therefore, was not open.

The relation between the arranged and obtained log reinforcer ratios for Bird 112 for each sequence is shown in Figure 1. This bird's performance was representative of all other subjects' performances. It can be seen in the top panels that in general the obtained reinforcer ratios were more extreme than the arranged reinforcer ratios. Note that Sequence 1 was the inverse of the other two sequences. The lower panels show the log response- and time-allocation ratios as a function of session number for each of the three sequences for Bird 112. Response and time ratios were very similar throughout all sequences, and in general they followed obtained reinforcer ratios.

The main purpose of the present experiment was to examine the contribution of both current- and previous-session reinforcers on present-session behavior. Thus, we fitted the obtained data to Equation 2. As appropriate for this equation, the data used were the log response ratios for all 31 sessions of each sequence, and for each session, the independent variables were the log reinforcer ratio in the current session and those from the previous nine sessions (including, where appropriate, sessions prior to the start of the sequence). Each iterative fit was run for at least 40,000 iterations, using the QuattroPro[®] Optimizer.

The results of fitting Equation 2 to the data for each subject in each sequence are shown in Table 1, and are shown averaged across subjects in Figure 2. Estimates of sensitivity to changes in the obtained reinforcer ratio at each of Lag 0 to Lag 9 and bias values according to Equation 2 are shown in Table 1 for each bird. The data were well described by Equation 2, with percentages of variance accounted for greater than 95% for 35 of the 36 fits. Bias ($\log c$) values were generally small, with values in the range ± 0.25 for 28 of the 36 fits, and an overall mean $\log c$ value of -0.03 for response measures and 0.07 for time measures. Sensitivity decreased systematically as a function of lag for all conditions (Figure 2), showing that recent-session rein-

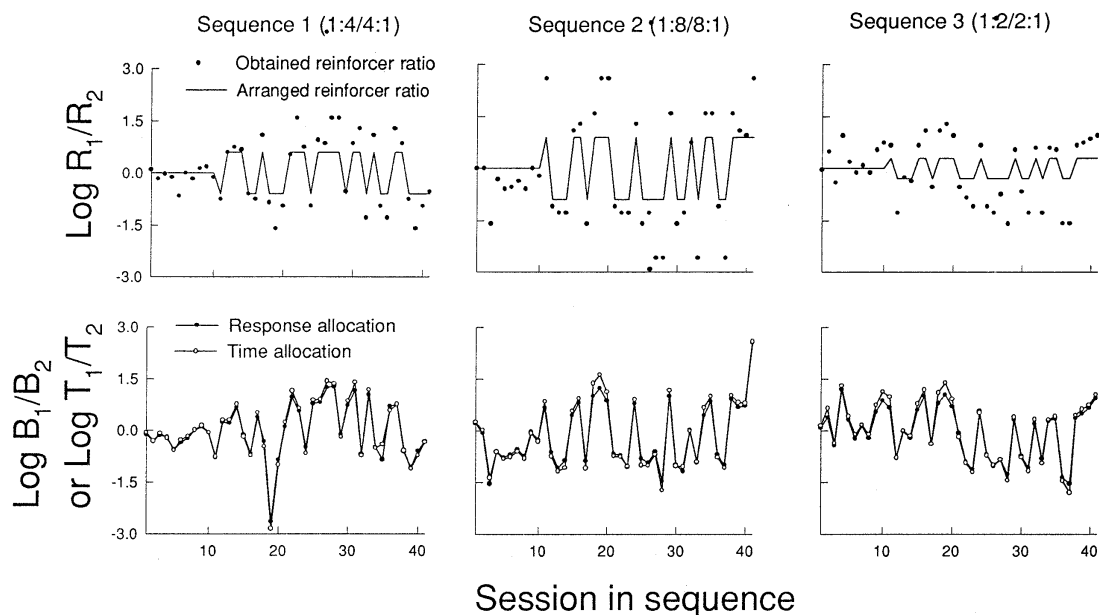


Fig. 1. Log arranged and obtained reinforcer ratios and log response- and time-allocation ratios as a function of the session number in the pseudorandom binary sequence for Bird 112, for all conditions of Experiment 1.

forcer ratios affected current behavior more than did more distant reinforcers. For all birds, the highest sensitivity value was always at Lag 0 (the present session).

The estimates of sensitivity calculated for Lag 0 showed that time-allocation measures were more sensitive to reinforcer-ratio changes than were response-allocation measures in 16 of the 18 pairs of fits (significant on a sign test at $p < .05$), but the sensitivity differences were not significantly different for any other lag. For Sequence 1, the mean sensitivity value for Lag 0 across birds was 0.55 for response allocation and 0.63 for time allocation; for Sequence 2, these values were 0.67 and 0.75; and for Sequence 3, they were 0.78 and 0.87. Thus, the differences between response- and time-allocation sensitivities at Lag 0 were similar to those reported for nonstable choice performance (Davison & Hunter, 1979; Hunter & Davison, 1985) and also for steady-state concurrent VI VI schedule performance (Baum, 1979; Taylor & Davison, 1983).

According to a nonparametric test for trend (Ferguson, 1971), sensitivity values calculated for both response and time measures at Lag 0 increased significantly as a function of the number of exposures to the sequence

(both $p < .05$). That is, behavior became significantly more sensitive to the reinforcer frequencies obtained in the present session as a function of the number of exposures to the random sequence. There was no significant change in Lag 0 sensitivities as a function of the reinforcer ratio arranged. There was also no evidence of any significant change in Lag 1 sensitivity as a function of training ($p > .05$, trend test).

When assessed using a sign test across subjects, sensitivity values for response and time allocation, respectively, were greater than zero up to Lags of 3 and 2 in Sequence 1, to Lags 2 and 1 in Sequence 2, and to Lag 2 for both measures in Sequence 3. However, such an assessment is very conservative, given that it rests upon the sensitivity value for a single subject becoming negative (given the small number of subjects). Given the small parameter values and the likely variance in the sensitivity estimates, this procedure could underestimate the general degree of control by reinforcers in previous sessions. A second method of assessment is the average number of lagged sessions over which sensitivity continued to be positive. Again, for responses and time, respectively, these values were 5.7 and 4.7 sessions in Sequence 1, 4.2 and 3.0

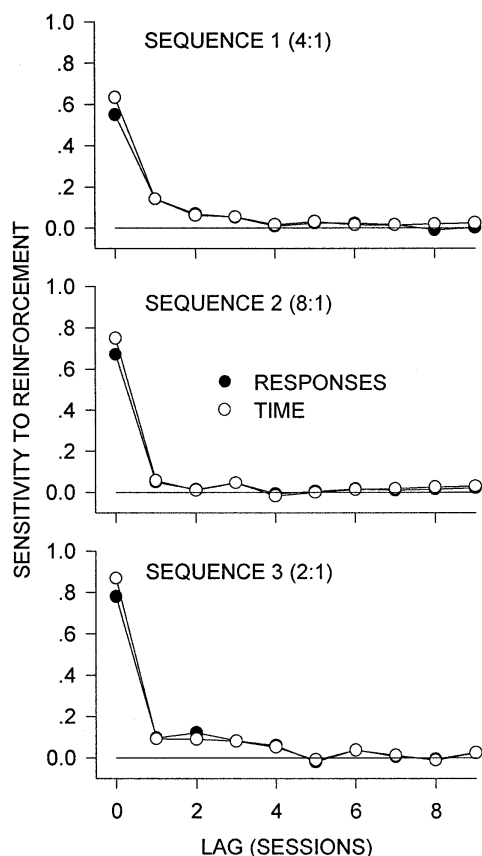


Fig. 2. Sensitivity to reinforcement as a function of the number of sessions lag between reinforcer-ratio input and current performance in Experiment 1. The data have been averaged over the 6 subjects.

sessions in Sequence 2, and 4.8 and 4.0 sessions in Sequence 3. A third method of assessment would be to ask, at what lag value did the sensitivities summed across lags cease to be numerically less than the cumulated sensitivity at Lag 9? These values, averaged over subjects, were for Sequence 1, 5.8 and 7.8; for Sequence 2, 5.2 and 5.7; and for Sequence 3, 5.7 and 5.8 for responses and time. This last assessment, which is closer to asking at what point cumulative sensitivity reaches its asymptotic value, provides a set of values that are significantly greater (sign test, $p < .05$) than the other two, more conservative, methods.

Davison and McCarthy (1988) showed that the asymptotic value of sensitivities cumulated over lags was the sensitivity value that should be observed under stable-state condi-

tions, and the values observed in the present data are similar to those for stable-state data. The mean asymptotic sensitivity for response- and time-allocation measures were, respectively, for Sequence 1, 0.86 and 1.03; for Sequence 2, 0.84 and 0.94; and for Sequence 3, 1.18 and 1.23. Asymptotic time-allocation sensitivities were greater than response-allocation sensitivities for all subjects in Sequence 1 and for 5 of the 6 subjects in Sequences 2 and 3 (a total of 16 of 18 comparisons, which is significant at $p < .05$ on a sign test). There was no significant relation between asymptotic sensitivity values as a function of either the sequence number or the arranged reinforcer ratios ($p > .05$).

DISCUSSION

The system arranged by the concurrent independent schedules was shown to be partially closed for the 2:1 and 8:1 reinforcer ratios. The extent to which this affected the results remains to be determined in a comparison with Experiment 2.

Although asymptotic response- and time-allocation sensitivity values did not change either as a function of the number of exposures to the sequence or as a function of the arranged reinforcer ratio, there were significant increases in the Lag 0 sensitivities to reinforcement as a function of sequence number only. We can tentatively conclude, therefore, that continued exposure to randomly changing reinforcer ratios leads to a progressive enhancement of control by the reinforcers delivered in the current session, with some concomitant decrease in the control by the reinforcer ratios in previous sessions. The latter conclusion is by implication, however, because no significant decreases in control by reinforcers at lags greater than 0 were found. Presumably, this nonsignificance is simply due to the small estimates of lag > 0 sensitivities in combination with the natural variance in these estimates. There was no significant relation between Lag 0 sensitivity values and arranged reinforcer ratios.

In general, these results agree with those of Hunter and Davison (1985) in two respects. First, at least in initial exposures to the random sequence, control by reinforcers in sessions lagging by two or three can be demonstrated. However, it was evident that sensitivity values in sessions greater than Lag 3 did

Table 1

Results of fits to Equation 2 for each subject and for all conditions of Experiments 1 and 2. In each case the a value (for each lag), the bias ($\log c$), and the percentage of variance accounted for by each fit (%VAC) are given. The data for Bird 111 in Sequence 4 are not given because this subject was new in this condition.

Bird	Measure	Sensitivity at lag (sessions)										$\log c$	%VAC
		0	1	2	3	4	5	6	7	8	9		
Sequence 1: Reinforcer ratio = 1:4/4:1													
111	Responses	0.50	0.09	0.10	0.07	0.09	0.04	-0.01	0.00	0.08	-0.01	0.10	99.4
	Time	0.64	0.14	0.09	0.06	0.09	0.03	-0.07	0.03	0.16	0.02	0.07	99.5
112	Responses	0.66	0.11	0.04	0.05	0.04	0.00	0.01	-0.00	0.02	-0.00	-0.06	99.1
	Time	0.71	0.08	0.08	-0.01	0.09	0.02	0.01	-0.01	0.06	0.01	-0.05	99.2
113	Responses	0.56	0.14	0.07	0.07	0.04	0.04	0.01	-0.01	-0.02	-0.05	-0.05	98.9
	Time	0.62	0.12	0.08	0.07	0.04	0.04	0.02	-0.02	-0.06	-0.05	0.28	99.3
114	Responses	0.64	0.18	0.02	0.09	-0.10	-0.00	0.10	0.09	-0.05	0.06	-0.06	99.7
	Time	0.79	0.21	0.04	0.09	-0.08	-0.02	0.08	0.08	-0.00	0.08	-0.18	98.9
115	Responses	0.54	0.16	0.09	0.03	0.00	0.02	0.02	0.01	0.00	-0.01	-0.13	98.9
	Time	0.55	0.13	0.05	0.06	0.01	0.03	0.04	0.01	0.03	0.02	0.01	98.7
116	Responses	0.40	0.17	0.08	0.00	-0.01	0.04	0.01	0.01	-0.09	0.02	-0.21	84.0
	Time	0.50	0.17	0.05	0.06	-0.05	0.09	0.02	0.06	-0.06	0.08	0.17	99.6
Sequence 2: Reinforcer ratio = 1:8/8:1													
111	Responses	0.68	0.01	0.01	0.05	-0.03	-0.01	-0.01	0.01	0.01	-0.01	0.46	99.4
	Time	0.76	0.03	0.01	0.05	-0.01	-0.01	0.00	0.03	0.05	-0.00	0.62	99.6
112	Responses	0.62	0.11	0.02	0.03	0.02	0.00	0.04	0.07	0.06	0.10	0.03	99.7
	Time	0.72	0.10	0.05	0.01	0.01	0.00	0.04	0.08	0.04	0.12	0.06	99.7
113	Responses	0.65	0.05	0.03	0.00	0.01	-0.00	0.05	-0.01	-0.01	0.03	-0.19	99.7
	Time	0.72	0.05	0.02	0.01	-0.01	-0.00	0.06	0.01	0.01	0.05	0.10	99.5
114	Responses	0.67	0.04	0.01	0.08	-0.01	0.03	0.06	0.01	0.02	0.10	0.10	99.4
	Time	0.85	0.05	0.01	0.09	-0.06	0.01	0.04	0.04	0.06	0.16	-0.01	99.6
115	Responses	0.78	0.07	0.00	0.06	-0.01	0.02	-0.09	0.01	0.04	0.01	0.11	99.7
	Time	0.74	0.08	-0.00	0.07	-0.03	-0.00	-0.13	0.01	0.01	0.00	0.16	99.6
116	Responses	0.62	0.01	0.02	0.06	-0.02	-0.01	0.04	-0.03	-0.02	-0.10	-0.49	99.0
	Time	0.70	0.03	-0.00	0.04	0.01	-0.00	0.07	-0.06	-0.00	-0.15	-0.29	99.8
Sequence 3: Reinforcer ratio = 1:2/2:1													
111	Responses	0.77	0.04	0.06	0.04	0.06	0.01	-0.11	0.00	-0.10	-0.04	0.40	97.6
	Time	0.87	0.05	0.00	0.03	0.10	-0.02	-0.12	0.02	-0.09	-0.01	0.10	98.6
112	Responses	0.76	0.11	0.07	0.05	0.00	0.09	0.02	-0.06	-0.01	0.11	0.07	99.7
	Time	0.91	0.13	0.06	0.07	0.01	0.07	-0.00	-0.01	0.01	0.12	-0.07	99.2
113	Responses	0.65	0.16	0.10	0.10	0.05	-0.03	0.02	0.02	-0.03	-0.02	0.03	99.3
	Time	0.76	0.14	0.09	0.09	0.03	-0.01	0.03	0.03	-0.04	-0.00	0.33	99.6
114	Responses	0.81	0.14	0.06	0.15	-0.05	0.01	0.15	0.06	0.05	-0.05	0.01	99.4
	Time	0.98	0.13	0.03	0.16	-0.08	0.02	0.18	0.05	0.04	-0.08	-0.14	99.5
115	Responses	1.01	0.02	0.31	0.13	0.23	-0.21	0.09	-0.03	0.06	0.16	-0.15	95.2
	Time	0.83	0.03	0.21	0.11	0.17	-0.11	0.08	-0.05	0.03	0.12	0.20	98.0
116	Responses	0.68	0.10	0.13	0.02	0.06	0.01	0.06	0.04	-0.01	0.00	-0.49	96.6
	Time	0.85	0.07	0.14	0.02	0.07	-0.02	0.06	0.02	-0.01	-0.01	-0.14	98.0
Sequence 4: Reinforcer ratio = 1:4/4:1													
112	Responses	0.79	0.04	0.01	0.05	0.05	0.06	0.01	0.01	-0.02	0.05	0.38	99.5
	Time	0.86	0.02	-0.01	0.00	0.06	0.07	0.00	0.01	-0.02	0.07	0.48	99.6
113	Responses	0.61	0.03	0.06	0.04	0.02	0.02	0.04	-0.01	-0.02	0.04	0.09	99.5
	Time	0.86	0.02	-0.01	0.00	0.06	0.07	0.00	0.01	-0.02	0.07	0.48	99.7
114	Responses	0.80	0.07	0.06	-0.02	-0.01	-0.01	-0.00	-0.04	0.00	0.05	-0.00	99.4
	Time	0.97	0.06	0.04	-0.02	-0.00	-0.02	-0.00	-0.03	0.02	0.04	-0.01	99.6
115	Responses	0.80	-0.01	0.04	-0.02	0.01	-0.01	0.06	-0.08	0.01	-0.03	-0.20	98.5
	Time	0.73	-0.01	0.04	-0.01	0.03	0.03	0.08	-0.04	0.01	0.02	0.04	98.8
116	Responses	0.49	0.07	-0.03	0.06	0.01	0.02	-0.00	0.01	0.01	0.03	-0.32	99.6
	Time	0.62	0.07	-0.04	0.05	-0.01	0.00	0.02	0.01	0.00	0.01	-0.06	99.8

Table 1
(Continued)

Bird	Measure	Sensitivity at lag (sessions)										log c	%VAC
		0	1	2	3	4	5	6	7	8	9		
Sequence 5: Reinforcer ratio = 1:2/2:1													
111	Responses	0.65	-0.04	-0.00	-0.07	-0.07	0.03	0.00	-0.04	-0.01	0.00	0.30	98.9
	Time	0.74	-0.02	-0.03	-0.04	-0.05	0.04	-0.03	-0.01	0.01	0.03	0.58	98.7
112	Responses	0.94	0.07	0.01	0.06	0.02	0.01	-0.07	-0.01	-0.14	0.03	0.38	95.5
	Time	0.92	0.07	0.02	0.06	0.00	0.02	-0.04	0.03	-0.11	0.01	0.12	98.9
113	Responses	0.59	0.03	0.02	0.02	0.02	0.02	0.04	0.03	0.03	-0.03	0.25	99.5
	Time	0.72	0.05	0.04	0.03	0.03	0.01	0.03	0.04	0.05	-0.03	0.27	99.6
114	Responses	0.53	0.27	0.03	0.11	-0.01	0.04	-0.09	-0.02	0.18	0.06	-0.13	98.6
	Time	0.73	0.28	0.00	0.11	-0.02	0.03	-0.10	-0.02	0.25	0.04	-0.09	97.9
115	Responses	0.88	0.00	0.03	0.07	0.01	-0.12	-0.05	0.08	0.10	-0.10	-0.06	99.2
	Time	0.81	0.01	0.03	0.05	-0.05	-0.09	-0.03	0.04	0.07	-0.07	0.07	99.6
116	Responses	0.44	0.04	0.11	-0.00	0.04	0.00	0.07	0.01	0.03	0.11	-0.51	99.1
	Time	0.65	0.07	0.10	0.03	-0.03	0.00	0.08	0.06	0.03	0.07	-0.10	97.9
Sequence 6: Reinforcer ratio = 1:8/8:1													
111	Responses	0.43	0.17	0.14	-0.09	-0.00	0.06	-0.10	0.11	0.14	0.02	0.03	96.8
	Time	0.47	0.19	0.07	0.09	0.14	-0.00	0.03	0.18	-0.08	0.30	0.16	95.9
112	Responses	0.85	0.06	0.04	0.08	0.04	0.05	0.03	0.03	-0.02	-0.03	-0.16	99.6
	Time	0.83	0.06	0.05	0.08	0.02	0.04	0.01	0.02	-0.01	-0.04	-0.27	99.6
113	Responses	0.58	-0.01	-0.01	0.04	-0.04	0.06	0.05	0.00	0.00	0.02	0.12	99.8
	Time	0.68	0.00	-0.01	0.04	-0.02	0.06	0.05	0.00	0.00	0.02	0.15	99.6
114	Responses	0.61	-0.00	0.04	0.06	-0.01	0.06	-0.01	-0.05	-0.04	-0.01	-0.08	99.3
	Time	0.78	0.01	0.02	0.07	-0.02	0.06	0.02	-0.03	-0.05	-0.01	-0.08	99.5
115	Responses	0.76	0.02	0.06	-0.00	0.01	0.01	-0.02	-0.01	0.02	0.07	-0.01	96.6
	Time	0.73	0.03	0.05	0.01	0.01	0.01	-0.01	-0.03	0.02	0.06	0.11	99.1
116	Responses	0.61	0.06	0.05	0.01	0.01	0.02	0.04	0.00	-0.04	-0.00	-0.36	96.5
	Time	0.72	0.08	0.06	0.00	0.01	0.00	0.04	-0.01	-0.06	0.01	-0.19	99.4
Sequence 7: Reinforcer ratio = 1:4/4:1													
111	Responses	0.34	0.21	0.06	0.04	0.01	0.07	0.02	0.02	-0.02	0.03	-0.26	99.5
	Time	0.35	0.15	0.06	0.06	0.02	0.09	0.01	0.06	0.07	0.10	-0.24	98.1
112	Responses	0.76	0.07	0.06	-0.00	0.03	0.03	0.03	0.05	0.01	-0.01	-0.13	99.4
	Time	0.83	0.04	0.07	-0.01	0.03	0.02	0.02	0.05	-0.01	0.00	-0.16	99.6
113	Responses	0.65	-0.01	0.03	0.04	-0.02	0.03	-0.05	-0.02	-0.00	0.03	0.01	99.3
	Time	0.80	-0.02	0.01	0.04	-0.01	0.03	-0.05	-0.02	0.01	0.03	0.12	99.4
114	Responses	0.65	0.05	-0.01	0.00	-0.02	0.02	-0.02	-0.02	0.03	0.01	-0.30	98.2
	Time	0.85	0.05	-0.01	0.02	-0.02	0.01	-0.03	-0.02	0.01	-0.01	-0.08	99.5
115	Responses	0.75	-0.01	-0.01	-0.03	-0.05	0.11	0.01	-0.04	-0.00	-0.01	-0.25	98.2
	Time	0.64	-0.00	0.03	0.00	-0.04	0.06	0.02	-0.01	0.01	0.02	-0.11	98.6
116	Responses	0.74	0.04	0.03	0.05	-0.01	0.00	0.00	-0.00	0.03	-0.01	-0.49	99.3
	Time	0.83	0.00	0.02	0.02	-0.06	-0.02	-0.01	0.01	0.03	-0.02	-0.31	99.5

contribute in a quantitatively small way to asymptotic sensitivity, and that an accurate measurement of asymptotic sensitivity should include lags >3 , as suggested by Davison and McCarthy (1988). Asymptotic sensitivity values were similar to those reported in stable-state concurrent schedule experiments, agreeing with and clarifying the findings of Hunter and Davison. It seems that the pseudorandom sequence procedure is an effective way of quickly and accurately measuring stable-state sensitivity to reinforcement. Finally, consistent with this last conclusion, the usual

stable-state finding of time-allocation sensitivities being greater than response-allocation sensitivities was replicated here.

EXPERIMENT 2

Experiment 2 was a systematic replication of Experiment 1 that used nonindependent, rather than independent, concurrent scheduling. One additional sequence was added (Sequence 7), which was a direct replication of Sequence 4.

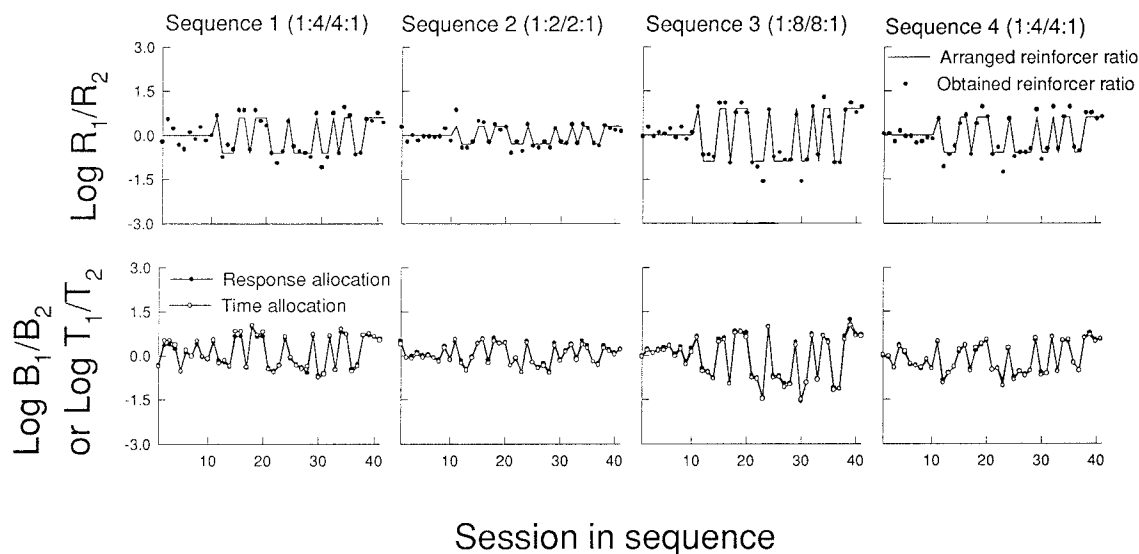


Fig. 3. Log arranged and obtained reinforcer ratios and log response- and time-allocation ratios as a function of the session number in the pseudorandom binary sequence for Bird 112, for all conditions of Experiment 2.

METHOD

Subjects and Apparatus

These were as described in Experiment 1. After Experiment 1 all subjects received at least 1 month's stable-state training on equally arranged concurrent VI VI schedules before commencing Experiment 2.

Procedure

Experiment 2 was exactly the same as Experiment 1, except that the concurrent schedules were arranged nonindependently (Stubbs & Pliskoff, 1969). When a reinforcer was arranged on one of the concurrent alternatives, the other schedule stopped timing until the arranged reinforcer had been obtained. Within an experimental condition, the concurrent-schedule probabilities of reinforcement varied from session to session according to the same 31-step pseudorandom sequence as in Experiment 1. In Sequences 4 and 7, the arranged reinforcer ratio was either 4:1 or 1:4, in Sequence 5 it was either 2:1 or 1:2, and in Sequence 6 it was either 8:1 or 1:8. The reinforcer ratio in each session was determined by the pseudorandom sequence.

RESULTS

The data presented were the same type as in Experiment 1, and Figure 3 shows the data

obtained from the four sequences of Experiment 2. Infinite reinforcer ratios occurred only in Sequence 6 (8:1) and not more than once for each subject. The obtained reinforcer ratios did not deviate significantly from the arranged reinforcer ratios (top panel of Figure 3) in any condition (sign tests, $p > .05$). Thus, in contrast to Experiment 1, the input log reinforcer ratios were independent of the output log response ratios. Time- and response-ratio measures (lower panels) again covaried closely over the sequences.

The results for Bird 111 in Sequence 4 were not used, because this was the first sequence to which this subject had been exposed. Equation 2 was fitted to both the log response and time ratios in the way described in Experiment 1, and the results of this analysis for all subjects are shown in Table 1 and summarized for the group in Figure 4. Estimates of sensitivity to changes in the obtained reinforcer ratio at each lag, inherent bias values, and the percentage of variance accounted for by each fit are shown in Table 1 for each bird. The data were well described by Equation 2. Over all four sequences, the percentage of variance accounted for was greater than 95% (overall $M = 98.8\%$). Bias values were generally small, with values between ± 0.25 calculated for 34 of the 46 fits (the overall mean was -0.07 for response measures and 0.04 for time measures).

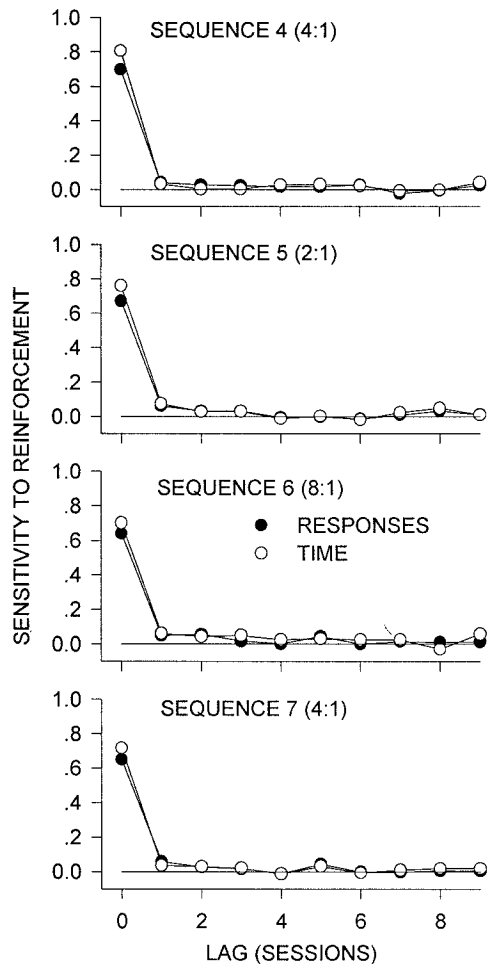


Fig. 4. Sensitivity to reinforcement as a function of the number of sessions lag between reinforcer-ratio input and current performance in Experiment 2. The data have been averaged over the 6 subjects, except in Conditions 4 and 5 in which 5 subjects were used.

Sensitivity parameters for Lag 0 were higher for time-allocation than for response-allocation measures for 17 of 23 comparisons (significant at $p < .05$ on a sign test), as found in stable-state concurrent schedule performance. The mean Lag 0 time- and response-allocation sensitivity values were, respectively, for Sequence 4, 0.81 and 0.70; for Sequence 5, 0.76 and 0.67; for Sequence 6, 0.70 and 0.64; and for Sequence 7, 0.72 and 0.65. These values were close to those observed in stable-state choice procedures (Taylor & Davison, 1983; Wearden & Burgess, 1982). On trend tests, there were no significant relations between Lag 0 sensitivity and either sequence

number or reinforcer ratio for either sensitivity measure.

Sensitivity values beyond Lag 0 were small, and, on a sign test across subjects, were not significantly different from zero for any lag beyond Lag 0 for either response- or time-allocation measures ($p > .05$). However, for 19 of 23 comparisons for response sensitivities and for 20 of 23 comparisons for time sensitivities, cumulated sensitivities at Lag 9 were greater than the sensitivity to Lag 0, indicating that sensitivities beyond Lag 0 were contributing significantly (sign test, $p < .05$ in both cases) to stable-state sensitivity. Cumulative sensitivities from nine lags were, for responses and time, respectively, Sequence 4, 0.70 and 0.80; Sequence 5, 0.84 and 0.96; Sequence 6, 1.0 and 0.99; and Sequence 7, 0.79 and 0.85. The average number of lagged sessions over which sensitivity continued to be positive for response and time allocation, respectively, were, Sequence 4, 4.2 and 2.0; Sequence 5, 4.3 and 4.5; Sequence 6, 4.0 and 5.3; and Sequence 7, 4.3 and 3.5. These values were very similar to those found in Experiment 1. The average number of lags at which the summed sensitivities across lags were less than the cumulative sensitivity at Lag 9 for response and time measures, respectively, were, Sequence 4, 6.6 and 7.6; Sequence 5, 5.0 and 4.8; Sequence 6, 7.5 and 6.8; and Sequence 7, 5.7 and 6.0. Again, these values are much the same as those obtained in Experiment 1, and suggest that there may be small but longer term effects of reinforcer ratios gained in previous sessions. Averaging across replications, a total of 14 of 18 cumulative time-allocation sensitivity estimates were greater than response sensitivity estimates, which is significant on a sign test at $p < .05$.

In addition, there was no evidence of any significant order effect on sensitivities cumulated to Lag 9 (nonparametric trend test, $p > .05$). When the sensitivities from Sequences 4 and 7 were averaged, a nonparametric trend test also showed that there were no significant trends ($p > .05$) in cumulative sensitivity as a function of the reinforcer ratio arranged.

DISCUSSION

In Experiment 2, obtained reinforcer ratios did not differ significantly from arranged reinforcer ratios, so the system was open, as the

oretically required by the type of analysis we carried out. Unlike Experiment 1, there was no effect of sequence number on Lag 0 sensitivities. But, like Experiment 1, sequence number did not affect cumulated sensitivities, and the arranged reinforcer ratio did not affect either Lag 0 or cumulated sensitivities.

Comparing Experiments 1 and 2, there were no significant differences between Lag 0 or between cumulated sensitivities for any reinforcer ratio (sign tests, $p > .05$), using the average 4:1 ratio data from Experiment 2. However, if just the Lag 0 differences between the first 4:1 reinforcer ratio in both experiments (Sequences 1 and 4) are calculated, all differences for both sensitivity measures were in the direction of greater sensitivity for Experiment 2 (five comparisons, $p < .05$ on a directional sign test). This supports our interpretation that there was decreased relative control by present-session reinforcer ratios at the start of the first sequence in Experiment 1.

A reasonable way of assessing the speed of learning in the present experiment is to calculate the percentage of the cumulative (Lags 0 to 9) sensitivities that are contributed by Lag 0. On average, these percentages were 72% and 81% for response and time allocation in Experiment 1 and 81% and 82% in Experiment 2. However, the means for Experiment 1 are deflated by low values for Sequence 1 (63% and 62%), and the mean values for Sequence 1 were the smallest of the set of averages over both experiments. This analysis supports our contention that there was some significant learning about the random nature of the sessions in Sequence 1 and an increase in present-session control at the expense of previous-session control in this sequence. On the average, then, after exposure to an environment that may change from session to session, about 80% of the control over both response and time allocation arises from the current session. But this percentage may be much lower after exposure to more constant environments. For example, in Hunter and Davison's (1985) data, an average of only 53% (PRBS 1) and 56% (PRBS 2) was contributed by Lag 0. The small difference between these is the result of a 10-month intermission, in which other stable-state experimental procedures were in operation, between exposures to the two sequences. These comparisons, then, seem to show that

exposure to randomly changing environments changes the location of control of choice from the present and previous sessions to mainly the present session. The comparison with the results reported by Hunter and Davison (1985) also indicates that exposure to infrequently changing environments may promote control by reinforcers in sessions prior to the present session.

There was no control by the size of the reinforcer ratio over the percentage of control by the current session's reinforcer ratio (non-parametric trend tests, $p > .05$) for either measure in both experiments. This result fully supports that of Mazur (1992), who reported no effect of the size of reinforcer ratios in concurrent VI VI schedules on speed of learning. However, the present results generalize his findings to learning rates across sessions rather than rates within sessions. Both Bailey and Mazur (1990) and Mazur and Ratti (1991) found differences in learning rates under different reinforcer ratios with ratio-based rather than interval-based concurrent schedules. The reason for this difference remains unclear.

It is evident from the differences in the percentage of control by Lag 0 and from the absolute values of Lag 0 sensitivities that performance changed when the pigeons were first exposed to the random sequence of reinforcer ratios, resulting in increased control by the reinforcers in the current session. This effect is consistent with results reported by Shettleworth and Plowright (1992), who found that pigeons were able to adapt to the frequency of change of environmental contingencies and to adjust a memory window to give different weightings to past and present events (see also Cuthill, Kacelnik, Krebs, Haccou, & Iwasa, 1990).

However, in the face of enhanced Lag 0 sensitivity values during initial exposure to randomly changing reinforcer ratios, a particularly interesting finding was that cumulative sensitivity did not change significantly. Although this result is not particularly strong, the implication that sensitivity is somehow conserved between different lags could have important implications. For example, it implies that the rapid assessment of stable-state sensitivity to reinforcement does not have to concern itself with adaptation to the frequency with which an environment changes. This

tentative suggestion, though, needs further research, as does the possibility that, with conservation of cumulative sensitivity, exposure to constant environments tends to decrease Lag 0 sensitivity.

Lag 0 response- and time-sensitivity values at different reinforcer ratios were not significantly different between experiments. Thus, whether independent or nonindependent scheduling is arranged made no difference to the results of the pseudorandom procedure, and the degree to which independent scheduling produced a closed system in Experiment 1 did not compromise the analysis. Furthermore, cumulative sensitivity values were also not significantly different between scheduling procedures. This finding is, at least in a negative sense, consistent with stable-state research in which differences in sensitivity values between independent- and dependent-scheduling procedures have not been reported. The reason for the lack of difference here, and the lack of effect of closed versus open systems, may lie in the fact that our analysis used obtained, rather than arranged, reinforcer ratios. Given that we found significant differences between arranged and obtained reinforcer ratios for two of the three Experiment 1 sequences, an analysis using arranged reinforcer ratios would have provided different results, and possibly would have shown significant differences between independent- and dependent-scheduling procedures. The present result is thus one further demonstration of the importance of using obtained reinforcer ratios in choice analyses (see Davison & McCarthy, 1988).

Given the excellent fit of Equation 2 to the present data, it is worth revisiting a suggestion made by Davison and Hunter (1979). They reasoned that if Equation 2 fit well, then the aggregate effects of all reinforcers prior to the current session would naturally be summarizable in a single variable: the log response (or time) ratio in the previous session. In this way, yesterday's dependent variable becomes a surrogate for today's independent variable, and yesterday's measurement of choice becomes, in a way, a psychometric measure of the state of the organism at the start of the next session.

The importance of using the pseudorandom sequence for such research cannot be overstated. Such sequences have no sequen-

tial dependencies within a short (here, 31-step) sample. Purely random sequences will not be effective because, over a relatively short sample, the mean is unlikely to be zero, sequential dependencies will occur, and there is a finite probability that, for example, all 31 steps would consist of one reinforcer ratio. Furthermore, of course, each subject is likely to be subjected to a different sequence. Finally, from a more behavioral perspective, in line with the results found here, long runs of one reinforcer ratio may well change the relative contributions of the reinforcer ratios of Lag 0 and earlier sessions.

There are several possibilities for further work using the pseudorandom procedure. The effects of session-to-session changes in a variety of different independent variables on choice could be assessed. For example, how would preference change within a session if the alternative with the larger magnitude or delay or quality of reinforcement, or the force required for responding, changed from session to session? These variables, which have well-known effects on stable-state choice, could be investigated much more efficiently using the pseudorandom procedure now that it has been validated for a range of reinforcer-frequency ratios.

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