DETERMINATION OF A BEHAVIORAL TRANSFER FUNCTION: WHITE-NOISE ANALYSIS OF SESSION-TO-SESSION RESPONSE-RATIO DYNAMICS ON CONCURRENT VI VI SCHEDULES

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Six pigeons were exposed to concurrent variable-interval schedules in which the programmed reinforcer ratios changed from session to session according to a pseudorandom binary sequence. This procedure corresponded to the stochastic identification paradigm ("white-noise experiment") of systems theory and enabled the relation between log response ratios in the current session and log reinforcer ratios in all previous sessions to be determined. Such dynamic relations are called linear transfer functions. Both non-parametric and parametric representations of these, in the form of "impulse-response functions," were determined for each bird. The session-to-session response ratios resulting from the session-to-session pseudorandom binary variations in reinforcer ratios were well predicted by the impulse-response functions identified for each pigeon. The impulse-response functions were well fitted by a second-order dynamic model involving only two parameters: a time constant and a gain. The mean time constant was 0.67 sessions, implying that the effects of abrupt changes in log reinforcer ratios should be 96% complete within about five sessions. The mean gain was 0.53, which was surprisingly low inasmuch as it should equal the sensitivity to reinforcement ratio observed under steady-state conditions. The same six pigeons were subjected to a similar experiment 10 months following the first. Despite individual differences in impulse-response functions between birds within each experiment, the impulse-response functions determined from the two experiments were essentially the same.

Key words: concurrent schedules, white-noise analysis, system identification, behavioral transfer functions, impulse-response functions, PRBS sequence, choice, pecking, pigeons

Interest in changes in behavior as a function of time or trials dates back to early work involving learning curves (see Mazur & Hastie, 1978) and cumulative records (Fester & Skinner, 1957). However, although accounts of behavior in transition have been relatively unsuccessful, approaches to predicting stable-state performance have been fruitful in a number of areas, particularly in the prediction of choice between different rates of reinforcers in concurrent schedules.

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The generalized matching relation (Baum, 1974), for example, relates response ratios (B_1/B_2) to reinforcer-frequency ratios (R_1/R_2) in terms of a power function:

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

where a and c are parameters.

The experimental data to which Equation 1 is fitted are typically obtained from experiments involving a series of abrupt ("step") changes from one pair of reinforcer schedules to another pair, with each pair being in effect until the behavior stabilizes. In the case of concurrent variable-interval (VI) schedule experiments, the change in response ratios following a step change in reinforcer ratios does not occur instantaneously but rather involves a relatively slow transition from a previous steady state to a new steady state (Davison & Hunter, 1979).

Consideration of the behavior immediately following a change, rather than just the final steady-state relation, gives rise to a number of questions. They are most easily considered in the language of systems theory (Eykhoff, 1974; Kailath, 1980). Within this theoretical system, the behavior ratio B_1/B_2 is considered the output of a system (here, the pigeon) when subjected to an input, the reinforcer ratio, R_1/R_2 . Similar approaches have been taken in the past by Johnson and Wheeler (1982), Krossner (1967), and Staddon (1964).

In systems theory, it is usual to refer to the change in output following a change in input as the *response* of a system. The way in which this response is spread over time since the change is referred to as the *dynamics* of the response. We can therefore ask:

1. What is the time course of the response to a change in input? Conventionally, it is thought that after some 15 to 30 sessions of training, the effects of a change in reinforcer ratio have diminished to the extent that the response ratios may be considered stable. The criteria used to establish when data are stable have been somewhat arbitrary. Quantification of the dynamics of the response to a step change in the reinforcer ratio should permit more meaningful stability criteria to be established.

2. How can the dynamics of a response to a change in input be described? In particular, does a dynamically linear transfer function give an adequate description, or is a more complicated, nonlinear representation required? Dynamic linearity implies that the dynamic response resulting from an input consisting of the sum of two inputs will be the same as the sum of the dynamic responses resulting from each input alone (see Kailath, 1980). Dynamic linearity also implies that the time course of the dynamic response remains constant for a constant form of input change. That is, the form of a response to a step change will be the same regardless of the size or direction of the step, and the same will be true of a response to an "impulse" (a brief change to a different input value). Furthermore, the amplitude of the dynamic response should be proportional to

the amplitude of the change in input, but should be unaffected by the initial level from which the input changed. Specific implications of dynamic linearity can be used to test for its adequacy as a model; for example, if the form of the dynamic response resulting from a step input change from A to B is not the same as that resulting from a step input change from B to A, then a linear dynamic model is inadequate.

3. Is the dynamic representation able to predict the steady-state (static) performance? In terms of systems theory, the value of the exponent in Equation 1 (which is sometimes referred to as a sensitivity parameter) is a measure of the static gain between log reinforcer ratios (input) and log response ratios (output). Static gain enters as a parameter into models of the dynamic response of systems, and so can be determined from experiments that vary reinforcer ratios. Differences between the static gains determined from steady-state and dynamic conditions could have important consequences for experimental design.

The objective of the present experiment was to quantify the dynamic component of the response of pigeons to abrupt changes in reinforcer ratios within the context of the concurrent VI VI schedule procedure. This was done by means that are routinely used in engineering contexts (e.g., Eykhoff, 1974; Goodwin & Payne, 1977; Kalaba & Spingarn, 1982), where they are referred to as "system-identification techniques." Although such techniques are occasionally either alluded to or applied in behavioral analyses (e.g., McFarland, 1971, 1974; McFarland & Houston, 1981; Toates, 1975, 1980), they are relatively unfamiliar in behavioral contexts. Because they were crucial to the success of the experiment reported here, they will be briefly outlined.

System Identification

The objective of system identification is to obtain a description of the dynamics of a system from measurements of the system's input and output. The description may be either in the form of numbers or in the form

of dynamic equations; these are referred to as parametric and nonparametric representations, respectively. In either case, it can be shown that if the system is dynamically linear, there will be some function $h(\sigma)$ such that the output $y(t)$ can be predicted from the input $x(t)$ via the convolution integral (Kailath, 1980):

$$y(t) = \int_0^T h(\sigma) x(t-\sigma) d\sigma. \quad (2)$$

In words, Equation 2 says that the output at time t can be predicted by taking the inputs at times between 0 and T units before t , and multiplying each of them by a quantity h , and adding the resulting products. The quantity h varies as a function of the time (σ) before t . This function, $h(\sigma)$, is referred to as the *kernel* of Equation 2, or alternatively as the system filter, the inverse Laplace transform of the transfer function, or as the impulse-response function (IRF) (Eykhoff, 1974). The IRF can be considered as the noise-free response of the pigeon to a unit impulse input—that is, a single session in which the input (log reinforcer ratio) is 1.0, preceded and followed by sessions in which the input is 0. Numerical convolution (i.e., numerical approximation to Equation 2) of the IRF with the input log reinforcer ratio sequence gives a prediction of the output (log response ratio) sequence. It can be shown that the area under an IRF should equal the “static gain” of the system—that is, the constant of proportionality relating output to input under steady-state conditions. As was noted earlier, the static gain is the sensitivity parameter in Equation 1. It is usually the case that $h(\sigma)$ becomes trivially different from zero after some σ which may, without loss of generality, determine the integral limit T .

The classical engineering approach to systems identification involves the use of sinusoidal changes in the input. Although such input variations have been used in the study of dynamic schedule performance (e.g., Johnson & Wheeler, 1982; Krossner,

1967; Staddon, 1964), because they are periodic they may, for a system capable of prediction, yield dynamics that are quite unrepresentative of dynamics resulting from transient stimuli such as steps.

A recent innovation in the analysis of dynamic systems uses, instead, stochastic (i.e., unpredictable) changes in input (e.g., Bendat & Piersol, 1980; Marmarelis & Marmarelis, 1978). The use of such stochastic system-identification techniques is often called the “white-noise” approach (Marmarelis & Marmarelis, 1978). These techniques are readily implemented using recent special-purpose computer languages such as NEXUS (Hunter & Kearney, in press). They provide not only a powerful set of experimental tools, but also a set of analytic methods that are robust in the presence of noise (output fluctuations unrelated to the input; Kalaba & Spingarn, 1982). This latter feature is conspicuously absent in recent deterministic analyses of behavioral dynamics (e.g., Herrnstein, 1979; McDowell, 1980; McDowell & Kessell, 1979; Myerson & Miezin, 1980).

A particularly simple stochastic identification technique involves presenting an input that varies between two values according to a pseudorandom binary sequence (PRBS; Eykhoff, 1974). The PRBS is simple to implement because it has only two values and yet is sequentially random. In the terms used in system-identification theory, this means that it has a white (flat) power spectrum or, equivalently, that it has an autocorrelation function in which nonzero lags have a value of zero (Bendat & Piersol, 1980). The PRBS also has the useful property, by virtue of its binary probability density function, of having the largest variance for the least range of any possible input function. The choice of a suitable PRBS depends on the time scale over which the dynamic system is to be studied. Algorithms for generating PRBSs are given by Hunter (1980), and a general technique for generating a very wide class of stochastic sequences, including PRBSs, is given by Hunter and Kearney (1983a).

In the present experiment, the interest

was in the session-to-session dynamics of the behavior ratios on concurrent VI VI schedules. Thus, a PRBS was used which, from session to session, changed the concurrent VI VI reinforcer ratio between two values. The values were chosen to be the reciprocal of each other so that, when logarithmically transformed, they formed a PRBS that varied symmetrically about zero. This choice also meant that both ratios could be implemented with the same two VI schedules. A PRBS generated by the feedback shift-register method (Eykhoff, 1974, p. 388) of the type used in the present experiment has a length that is one step less than a power of 2 (i.e., 15, 31, 63, 127, etc.). The length of the PRBS should be at least twice the value of T in Equation 2 (Hunter, 1980). A PRBS of length 31 was therefore chosen because experience of concurrent VI VI schedules has shown that the response-ratio dynamics resulting from a step change in reinforcer ratio is largely over in less than 15 sessions (Davison & Hunter, 1979; Stubbs & Pliskoff, 1969).

In order to determine the consistency of the present approach, the PRBS sequence was repeated 10 months later using the same subjects.

METHOD

Subjects

Six homing pigeons, numbered 2/1 to 2/6, with 4 years' experience on concurrent VI schedules, served as subjects. The birds were housed in individual cages containing water and grit, and they were fed mixed grain following each daily experimental session to maintain them at $80\% \pm 15\%$ g of their free-feeding body weights.

Apparatus

All experimental events were controlled by solid-state logic situated in a different room from the experimental chamber. Electromagnetic counters recorded the data. The sound-attenuated chamber was 35 cm high, 30 cm deep, and 35 cm wide and was fitted with an exhaust fan that helped mask exter-

nal noise. The chamber contained two response keys, 2 cm in diameter, 13 cm apart, and 26 cm from the wire-mesh floor. Each key could be illuminated from behind. A peck on these keys was recorded only if it exceeded a minimum static force of 0.1 N through a distance of 1.5 mm. The maximum displacement of each key was 4.5 mm. In addition to the tactile and auditory feedback resulting from the key itself, each effective peck produced a 35-ms offset of the keylight and a click from a relay mounted behind the front panel. A hopper containing wheat was situated midway between the two keys and 10 cm from the floor. Reinforcement was 3-s availability of the illuminated hopper while the keylights were off. No other lights were used in any part of the experimental environment, and pecks on darkened keys were ineffective. Sessions were conducted 7 days per week. They were started at approximately the same time each day and were terminated after 40 reinforcers had been delivered.

Procedure

Because the subjects had extensive experience on concurrent VI VI schedules, no preliminary training was necessary. The schedules were independently arranged, and each consisted of intervals randomized from the first 12 terms of an arithmetic progression in which the shortest interval was one twelfth the mean interval. A changeover delay of 1.5 s was arranged throughout the experiment. The experimental conditions (Table 1) were changed for each pigeon simultaneously.

The pigeons were first trained on concurrent VI 240 s VI 60 s for 12 sessions. A 31-step PRBS (Table 1) comprising concurrent VI 240 s VI 60 s and concurrent VI 60 s VI 240 s was then introduced. Each session was a separate step in the sequence, and so the entire sequence took 31 sessions to complete. This sequence of 31 sessions will be denoted PRBS-1 to distinguish it from a second sequence (PRBS-2) to which the pigeons were exposed 10 months later. In the period between PRBS-1 and PRBS-2,

Table 1

Sequence of concurrent VI VI schedules used in session sequences PRBS-1 and PRBS-2. The mean of the VI schedules is given in seconds. Each session represents one step in each of the 31-step PRBSs.

Session	PRBS-1		PRBS-2	
	Key 1	Key 2	Key 1	Key 2
1	60	240	60	240
2	240	60	60	240
3	240	60	60	240
4	240	60	240	60
5	60	240	240	60
6	60	240	60	240
7	240	60	240	60
8	60	240	240	60
9	60	240	240	60
10	60	240	60	240
11	240	60	240	60
12	60	240	60	240
13	240	60	240	60
14	60	240	60	240
15	240	60	60	240
16	240	60	60	240
17	240	60	60	240
18	240	60	240	60
19	60	240	60	240
20	240	60	60	240
21	240	60	240	60
22	60	240	60	240
23	240	60	240	60
24	60	240	240	60
25	60	240	60	240
26	240	60	60	240
27	240	60	240	60
28	60	240	240	60
29	60	240	240	60
30	60	240	240	60
31	60	240	240	60

the birds were trained on a range of concurrent VI schedules in another experiment. Prior to the introduction of PRBS-2, the birds were trained for 26 sessions on concurrent VI 60 s VI 240 s. PRBS-2 was exactly the same as PRBS-1 except that the schedules were reversed and PRBS-2 started one step ahead of PRBS-1. The sequence of schedules that comprised PRBS-1 and PRBS-2 are shown in Table 1.

RESULTS

The response, time, reinforcer, and changeover data for each session during PRBS-1 and PRBS-2 are shown in Appen-

dix A and Appendix B, respectively. In the following analysis, the input is the logarithm (base 10) of the reinforcer ratio, and the output is the logarithm (base 10) of the response ratio. These transformations were used to make the output a linear function of the input under steady-state conditions (see Equation 1).

One of the first questions that must be answered before proceeding with the input-output analysis of any system is the extent to which the system may be considered open or closed loop (Kailath, 1980; McFarland, 1971). If the pigeon was altering the dynamics of the input, the system would have to be considered as closed loop, and the dynamics of the obtained input could be different from the dynamics of the arranged input. As was explained in the introduction, the arranged input is "white" in that it has no sequential dependencies. If it can be shown that the obtained input is also "white," the simpler open-loop analysis is justified. It should be noted here that the way in which the concurrent schedules are arranged bears on this question. A PRBS sequence using dependent concurrent VI schedules would be more likely to produce an obtained input that is white than would a sequence using independently arranged concurrent schedules (as used here). Schedules in which reinforcer rates are a function of response rates (for example, fixed- or variable-ratio schedules) will demand a closed-loop analysis.

Input autocovariance function. The sequential dependencies in a system can be measured by means of the autocovariance function, which plots the extent of the covariance between the current value of the independent variable (input) and its value σ units ago, as a function of σ , which is referred to as the "lag" (see Bendat & Piersol, 1980). If there are no sequential dependencies (that is, the sequence is white), then the autocovariance will be zero for all lags greater than zero. The autocovariance at lag zero is simply the variance of the sequence. Nonzero covariance at lags greater than zero indicates that one part of the sequence is correlated with (dependent on) previous parts of the se-

Fig. 1. The obtained log reinforcer ratio (input) autocovariance functions for the individual birds from the sequence of sessions referred to as PRBS-2.

quence (Bendat & Piersol, 1980).

The arranged input autocovariance at lag zero (the PRBS variance) was 0.36 for both PRBS-1 and PRBS-2. The inputs obtained by the pigeons had variances that were typically the same as the arranged input variances, but for some birds they were a little lower (e.g., 0.27 for Bird 2/1 in PRBS-2) and for others a little higher (e.g., 0.42 for Bird 2/2 in PRBS-2). Higher input variances result in larger signal-to-noise ratios, which in turn result in better estimates of the system dynamics (Bendat & Piersol, 1980).

Figure 1 shows the obtained input autocovariance functions determined for lags of up to 15 sessions for each bird. Similar functions were obtained from an analysis of PRBS-1. Because subsequent analyses do not assume that the input is white, it is sufficient to say that all six functions are close to, but not exactly, white. Inasmuch as the arranged input is exactly white, significant departures from whiteness in the obtained input would suggest that closed-loop effects had occurred. Evidently, they did not.

Output autocovariance function. It can be shown that if the input to a system is white and the output is also white, then the relation between input and output is either static (nondynamic), involves a pure delay, or is

Fig. 2. The log response ratio (output) autocovariance functions for the individual birds from the sequence of sessions referred to as PRBS-2.

nonexistent (Bendat & Piersol, 1980). Figure 2 shows the output autocovariance function for each bird with up to 15 sessions' lag for PRBS-2 (the PRBS-1 output autocovariance functions were similar). These functions, unlike those shown in Figure 1, clearly show the presence of sequential dependencies in the output. The dependencies appear to have died out after 10 to 15 sessions.

Impulse-response functions. Having established that a dynamic relation is likely to have existed between the input and the output, it remains to determine it. As explained in the introduction, the dynamics of a linear system can be represented by the impulse-response function (IRF), which is symbolized as $h(\sigma)$ in Equation 2. IRFs may be estimated using either parametric or nonparametric techniques. Figure 3 shows the nonparametric IRFs for each bird for both PRBS-1 and PRBS-2 determined via a parametric approach in which a second-order autoregressive moving-average (ARMA) model (Box & Jenkins, 1976) was fitted between the input and output data using a nonlinear least-squares minimization technique (Hunter, 1980; Shanno & Phua, 1976). The IRFs are obtained from the ARMA representation by polynomial division of the moving-average terms by the autoregressive terms (Box &

Fig. 3. Impulse-response functions (IRFs) determined from second-order autoregressive moving-average (ARMA) models estimated by nonlinear minimization for each bird's data from both sequences of sessions (PRBS-1 and PRBS-2).

Jenkins, 1976). A second-order ARMA model was chosen because a third-order model had too many free parameters, and a first-order model accounted for less output variance. The ARMA approach to determining the IRFs was chosen in preference to a direct nonparametric method (e.g., Hunter & Kearney, 1983b) because it enabled initial conditions (the state of the inputs immediately prior to the start of the PRBSs) to be readily included (see Box & Jenkins, 1976). Such initial conditions are difficult to incorporate in a direct nonparametric approach.

The proportion of the variance in the log response ratios accounted for by the IRFs shown in Figure 3 ranged from 70% to 96% (mean 85%). For comparison, the variance

Fig. 4. The input (log obtained reinforcer ratio), the output (log response ratio), and the output predicted by convolution of the IRF with the input for Bird 2/2 from one sequence of sessions (PRBS-2). The residuals (predicted output minus actual output) are also shown.

accounted for by Equation 1 (a static model) ranged from 28% to 70% (mean 48%). Figure 4 shows the output (log response ratio) for Bird 2/2 in PRBS-2 together with the output predicted (via numeral convolution, see introduction) for that bird using the IRF shown in Figure 3.

DISCUSSION

Although Skinner (1938) appears to have been the first to study the effect of periodically fluctuating reinforcer rates on performance, it was Staddon (1964) who first considered such schedules to be inputs to a dynamic

behavioral system. Since then, a number of studies (e.g., Farmer & Schoenfeld, 1967; Johnson & Wheeler, 1982; Kello, Innis, & Staddon, 1975; Krossner, 1967; McDowell & Sulzen, 1981; Staddon, 1967; Staddon & Frank, 1975; Starr & Staddon, 1974) have employed periodic schedules. The approach of many of these studies was to consider the organism as a system (black box) containing dynamic components that operate on inputs (i.e., reinforcer schedules) producing outputs (i.e., responses) that depend not only on current but also on past inputs. The objective of these studies was to identify the dynamics of the system from its response to sinusoidally varying inputs of various frequencies.

Because of the shortcomings of the classical sinusoidal approach mentioned in the introduction, the present study used stochastic system-identification techniques in an attempt to characterize the dynamics of performance on concurrent VI VI schedules. The approach yielded a representation of the dynamics in the form of an impulse-response function (IRF) which, when convolved with the input (log reinforcer ratios), provided a good prediction of the output (log response ratios).

The IRFs clearly showed that the log response ratio measure was not simply a function of the log reinforcer ratio in the current session; that is, it was dynamically related to the log reinforcer ratios in previous sessions. Furthermore, the data could be described reasonably well by functions derived under the assumption that the dynamic response is linear.

A number of features are apparent from the IRFs shown in Figure 3. First, the dynamics have clearly died out by the 10th sessional lag for all birds. Second, the time course of the IRFs appears similar for all birds. Third, the areas under the IRFs were different for different birds, whereas the PRBS-1 and PRBS-2 time course and areas for any given pigeon appeared similar.

In order to quantify these intuitive judgments, a parametric model of the dynamics is required. A simple dynamic

model suitable for representing the IRFs, which incorporates a measure of the area under the IRFs (i.e., the static gain of the system) as well as a measure of the time course of the IRFs, is the exponential IRF equation:

$$h(\sigma) = a\left(\frac{\sigma}{\tau}\right) \cdot \exp(-\sigma/\tau), \quad (3)$$

where σ is lag (i.e., time or sessions) and τ is the time constant of the system, here measured on a scale of sessions—the larger is τ , the more enduring the effects of a change in the input.

Using nonlinear minimization techniques (Hunter, 1980), Equation 3 was fitted to the IRFs (Figure 3) with σ taking the units of session number. Each IRF value was taken as representative of mid-session dynamics. Table 2 shows the gains (a) and time constants (τ) determined for each bird in both PRBS-1 and PRBS-2. The time constants ranged from 0.48 to 0.87 (mean 0.67) of a session.

It can be shown that the integral of an IRF gives the predicted response to a unit step change in input, $s(\sigma)$. The integral of Equation 3 is:

$$s(\sigma) = a - a\left(1 + \frac{\sigma}{\tau}\right) \cdot \exp(-\sigma/\tau). \quad (4)$$

It can readily be determined from Equation 4 that the response to such a step will be 96% of the final steady-state value (namely, a) within five time constants. Thus, within the context of the present experiment (i.e., particular session length, VI schedules, etc.), the prediction is that only three to five sessions are required, following a change in schedules, to bring the log response ratio to within 5% of its steady-state value. A similar number of sessions was found by Davison and Hunter (1979) in their investigation of sessional performance in concurrent VI VI schedules that progressively changed every six sessions. Both these results might seem rather fast considering the 15 to 30 sessions typically assumed to be necessary to achieve a steady state. Two points may be made. First, the steady-state criteria frequently used in concurrent-schedule research often

Table 2

The gain (a), time constant (τ), and percent variance accounted for (model %VAF) of the parametric dynamic model (Equation 3) fitted to the IRFs determined from the response and time ratio data of each bird in both session sequences (PRBS-1 and PRBS-2). The percent variance accounted for (%VAF) by the first 10 lags of the nonparametric linear dynamic impulse response function is also shown.

Bird	Cond.	Response ratio analysis				Time ratio analysis			
		%VAF	Model			%VAF	Model		
			a	τ	%VAF		a	τ	%VAF
1	PRBS-1	76.4	.71	.58	88.1	79.2	.59	.57	89.6
	PRBS-2	84.1	.67	.48	94.4	71.9	.72	.59	89.9
2	PRBS-1	89.2	.60	.58	88.6	84.9	.58	.57	91.6
	PRBS-2	85.5	.70	.62	97.6	87.3	.65	.61	97.8
3	PRBS-1	77.7	.33	.65	94.9	82.2	.58	.69	93.9
	PRBS-2	77.7	.49	.60	87.5	85.1	.63	.66	94.0
4	PRBS-1	84.4	.55	.87	96.9	83.1	.53	.84	97.4
	PRBS-2	87.7	.57	.68	97.4	88.6	.63	.68	98.5
5	PRBS-1	79.6	.45	.77	94.2	84.0	.46	.73	94.6
	PRBS-2	72.7	.35	.83	94.2	75.5	.35	.78	94.4
6	PRBS-1	53.5	.50	.79	90.1	67.3	.35	.62	89.0
	PRBS-2	78.1	.45	.61	94.4	81.1	.53	.62	96.1

require a minimum of 10 to 15 sessions before they *can* be met (e.g., Davison & Hunter, 1976). Second, such criteria will be sensitive not only to the dynamics resulting from a step change in the reinforcer ratio, but also to variations in performance due to other causes. Session-to-session variations in performance due to these unknown influences could be governed by dynamics similar to those associated with reinforcer-ratio changes. If this is the case, then dynamic models of session-to-session output variations with constant reinforcer ratios are likely to have time constants with values similar to those measured here.

The short time constants found in the present experiment also suggest that within-session fluctuations in interreinforcer intervals are highly likely to have an effect on session-to-session performance dynamics. Quantification of these within-session dynamics will require a stochastic identification protocol different from that used in the present experiment.

According to Equation 4, as σ becomes large, $s(\sigma)$ approaches the constant a (static

gain, or sensitivity to reinforcement). Thus, the parameter a used in Equations 3 and 4 should be equal to the exponent a of Equation 1. However, as shown in Table 2, the gains ranged from 0.33 to 0.71 (mean 0.53), and were thus smaller than those typically obtained from concurrent VI VI experiments involving step changes in reinforcer ratios (between 0.8 and 1.0; Baum, 1979). One explanation for the discrepancy is that gain might be underestimated by the present approach where sessional totals, rather than within-session measures, are used for analysis—the degree of change achieved by the middle of a session may be more than half that attained by the end of a session (Hunter, 1980). Alternatively, the gain may be reduced during random session-to-session changes in reinforcer ratios (see Davison & Hunter, 1979), or simply by relatively frequent changes in reinforcer ratios (Todorov, Oliveira Castro, Hanna, Bittencourt de Sa, & Barreto, 1983). Only a temporally more detailed study can resolve this issue.

Time-allocation dynamics. Thus far, the

analysis has focused on response ratios. In order to consider the possibility that changes in time-allocation ratios may precede or follow those in response ratios, the previous analyses were also conducted on the time-allocation data (see Table 2). The time constants (mean 0.66) and gains (mean 0.55) differed little from those obtained from the response-ratio analyses. There was therefore no evidence of a phase difference between sessional time-allocation ratios and response ratios.

In summary, a powerful experimental method for investigating behavioral dynamics using stochastic system-identification techniques has been presented here. We used it to examine the dynamic effect of changes in the reinforcer ratio provided by a concurrent schedule, which constitutes a first, limited, analysis of this type of performance. Dynamic interactions between different parameters of the same variables (for instance, overall reinforcer rate, which was constant here) and between different variables (for instance, reinforcer durations, delays, qualities, etc.) will have to be investigated before more global dynamic models can be identified. Quite apart from the intrinsic importance of dynamic analyses per se, there exists the interesting possibility of constructing inputs that are optimal in changing behavior from one stable state to another (Kalaba & Spingarn, 1982), thereby shortening the time required to conduct stable-state experiments.

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APPENDIX A

Number of responses emitted, total time allocated, reinforcers obtained, and transitions between Keys 1 and 2 in each session of PRBS-1.

Session	Responses		Time (secs)		Reinforcements		Transitions
	Key 1	Key 2	Key 1	Key 2	Key 1	Key 2	Key 1→2
<i>Bird 2/1</i>							
1	1518	1246	910	964	30	10	336
2	1023	1549	591	1101	8	32	265
3	768	1983	453	1225	8	32	234
4	852	1857	468	1182	9	31	291
5	1568	1434	722	969	29	11	314
6	2063	851	1012	643	31	9	238
7	1732	991	913	853	9	31	246
8	1794	1012	930	693	31	9	258
9	2300	878	1042	609	31	9	233
10	2225	711	1121	521	30	10	252
11	2328	936	1104	717	9	31	328
12	1988	774	1074	606	30	10	287
13	1851	881	981	770	9	31	383
14	2061	852	1013	616	31	9	346
15	2051	1374	869	822	9	31	470
16	1230	1853	630	1058	9	31	431
17	1159	1741	644	1080	9	31	378
18	865	1962	490	1171	9	31	289
19	1926	1075	937	690	29	11	322
20	1110	1777	562	1109	9	31	225
21	1408	1559	689	966	9	31	355
22	1502	1510	763	917	30	10	354
23	1007	1692	514	1168	9	31	325
24	1881	986	957	698	30	10	362
25	2474	589	1173	416	31	9	307
26	1542	1753	708	985	9	31	318
27	545	2395	365	1300	9	31	159
28	1902	844	965	653	31	9	276
29	2413	767	1100	549	31	9	330
30	2213	905	1030	593	29	11	267
31	2281	976	1042	604	30	10	329
<i>Bird 2/2</i>							
1	840	1030	834	1041	32	8	374
2	883	1535	721	1204	7	33	316
3	582	1670	537	1391	7	33	250
4	392	1698	370	1521	7	33	224
5	973	1212	862	1071	33	7	367
6	1267	724	1126	726	31	9	290
7	811	1123	841	1081	7	33	325
8	1223	1084	1091	826	32	8	263
9	1474	819	1309	594	32	8	298
10	1186	928	1214	689	31	9	421
11	1331	887	1206	729	8	32	326
12	1321	890	1265	639	32	8	315
13	1071	1076	1098	845	7	33	379
14	1301	1139	1104	810	32	8	338
15	1017	1381	788	1146	7	33	314
16	704	1523	664	1242	7	33	278
17	481	1676	427	1424	7	33	172
18	425	1803	425	1449	7	33	156
19	1067	1308	1004	998	32	8	358
20	1088	1167	963	963	7	33	331
21	630	1736	560	1350	7	33	252
22	1336	1073	1201	744	31	9	312
23	486	1457	554	1338	8	32	180
24	1135	867	1194	742	32	8	326
25	1629	532	1468	476	34	6	229
26	821	1394	726	1180	7	33	210
27	522	1324	492	1385	6	34	218
28	1150	761	1169	725	33	7	303
29	1188	589	1273	608	32	8	268
30	1308	564	1334	557	32	8	204
31	1389	610	1335	583	32	8	233

APPENDIX A—continued

Session	Responses		Time (secs)		Reinforcements		Transitions
	Key 1	Key 2	Key 1	Key 2	Key 1	Key 2	Key 1→2
<i>Bird 2/3</i>							
1	567	910	578	1285	31	9	290
2	711	942	724	1098	8	32	395
3	448	889	506	1294	8	32	249
4	412	845	486	1309	8	32	296
5	564	800	760	1198	32	8	300
6	962	754	1070	855	32	8	423
7	648	672	901	846	9	31	364
8	799	777	913	902	32	8	402
9	872	580	1157	729	32	8	371
10	945	557	1246	687	33	7	292
11	812	699	923	895	8	32	327
12	944	780	962	866	31	9	377
13	689	709	744	1010	9	31	322
14	846	716	937	947	32	8	355
15	710	814	696	1072	8	32	290
16	627	912	578	1200	8	32	340
17	495	867	466	1301	8	32	260
18	567	947	509	1302	8	32	290
19	772	714	884	956	32	8	356
20	716	752	823	1004	8	32	376
21	583	909	595	1230	9	31	301
22	844	815	913	958	32	8	357
23	590	912	554	1243	8	32	307
24	880	674	1012	791	32	8	380
25	979	781	1074	678	31	9	356
26	821	944	816	958	9	31	397
27	595	900	634	1161	8	32	359
28	748	772	947	926	32	8	382
29	972	679	1148	723	32	8	429
30	907	546	1344	550	33	7	344
31	953	680	1475	414	32	8	311
<i>Bird 2/4</i>							
1	711	987	754	1095	32	8	324
2	807	918	863	1088	9	31	290
3	628	988	757	1093	9	31	299
4	564	1038	629	1220	9	31	316
5	721	979	793	1177	31	9	362
6	846	745	960	874	31	9	398
7	855	819	935	957	9	31	494
8	861	784	959	916	31	9	458
9	955	611	1093	717	31	9	388
10	996	500	1119	621	31	9	366
11	861	702	1019	941	9	31	420
12	789	674	987	834	30	10	387
13	776	807	950	990	9	31	429
14	875	739	1002	849	31	9	389
15	764	821	869	1000	9	31	426
16	632	954	740	1153	9	31	386
17	516	1034	595	1252	9	31	340
18	477	1139	551	1308	9	31	336
19	698	930	812	1090	31	9	406
20	622	834	752	1040	9	31	406
21	608	993	741	1169	8	32	379
22	822	967	964	977	31	9	443
23	688	932	811	1068	9	31	453
24	791	835	963	912	31	9	449
25	946	664	1104	697	32	8	458
26	713	853	888	1005	8	32	457
27	523	925	717	1038	9	31	355
28	610	899	784	972	31	9	376
29	854	695	1013	763	30	10	405
30	925	584	1115	647	30	10	381
31	972	481	1205	546	30	10	380

APPENDIX A—continued

Session	Responses		Time (secs)		Reinforcements		Transitions
	Key 1	Key 2	Key 1	Key 2	Key 1	Key 2	Key 1→2
<i>Bird 2/5</i>							
1	914	1478	895	1097	32	8	599
2	886	1554	775	1194	6	34	549
3	802	1666	759	1198	7	33	540
4	755	1648	741	1204	7	33	513
5	617	1208	828	1286	32	8	372
6	1210	1006	1173	826	33	7	519
7	1163	1260	990	939	7	33	460
8	1291	1177	1098	835	33	7	438
9	1522	1102	1245	738	33	7	476
10	1624	887	1380	571	32	8	468
11	1277	1256	1056	881	7	33	480
12	1256	1249	1102	903	33	7	488
13	1154	1186	952	905	8	32	527
14	1542	1264	1149	838	33	7	561
15	1468	1288	1076	909	7	33	512
16	1126	1661	832	1162	7	33	423
17	875	1736	669	1277	7	33	415
18	802	1645	663	1300	7	33	422
19	1143	1380	1045	967	33	7	441
20	1001	1747	749	1240	7	33	520
21	979	1772	704	1251	7	33	452
22	1534	1778	1012	1008	33	7	511
23	1134	1764	802	1164	7	33	502
24	1375	1490	1049	910	32	8	545
25	1778	1035	1286	622	32	8	521
26	1238	1349	1021	965	7	33	452
27	966	1998	733	1186	7	33	460
28	1448	1657	1018	935	32	8	460
29	1766	1067	1292	644	32	8	592
30	1885	1035	1317	646	33	7	513
31	1769	805	1418	527	33	7	410
<i>Bird 2/6</i>							
1	549	1067	733	1264	32	8	345
2	726	800	740	1064	9	31	445
3	775	700	799	1085	8	32	450
4	554	873	670	1163	8	32	336
5	968	820	926	962	30	10	459
6	860	648	974	915	32	8	488
7	900	626	929	947	8	32	489
8	863	649	921	928	32	8	416
9	1097	446	1052	801	32	8	507
10	1356	433	1231	675	33	7	422
11	1088	445	1002	801	9	31	403
12	1121	450	1188	680	32	8	388
13	582	434	919	923	8	32	338
14	461	586	1024	921	32	8	290
15	494	602	817	992	9	31	246
16	498	560	799	1035	9	31	351
17	454	613	745	1114	8	32	368
18	416	695	671	1167	8	32	322
19	600	537	888	940	31	9	390
20	515	858	743	1267	7	33	313
21	445	969	620	1173	9	31	297
22	681	672	921	934	31	9	312
23	543	1010	634	1205	8	32	272
24	919	515	1039	765	31	9	367
25	1073	474	1117	740	32	8	447
26	737	828	722	1055	9	31	318
27	488	1133	538	1188	9	31	210
28	511	1077	747	1233	31	9	196
29	896	495	1101	740	32	8	372
30	998	491	1178	736	32	8	335
31	773	387	1255	677	32	8	244

APPENDIX B

Number of responses emitted, total time allocated, reinforcers obtained, and transitions between Keys 1 and 2 in each session of PRBS-2.

Session	Responses		Time (secs)		Reinforcements		Transitions
	Key 1	Key 2	Key 1	Key 2	Key 1	Key 2	Key 1→2
<i>Bird 2/1</i>							
1	2237	506	1159	390	31	9	205
2	2507	537	1217	355	31	9	216
3	2329	497	1193	399	32	8	224
4	2489	789	1260	571	10	30	365
5	1436	1501	706	943	9	31	349
6	1720	1238	805	779	31	9	330
7	1616	1366	699	997	9	31	388
8	1219	1638	557	1085	9	31	367
9	1228	1592	523	1097	9	31	391
10	1241	2181	547	1317	14	26	447
11	1784	1400	825	928	13	27	491
12	1748	890	843	746	31	9	346
13	1683	1043	786	871	9	31	425
14	1904	920	948	657	28	12	436
15	2089	658	1113	498	31	9	312
16	2060	599	1058	501	31	9	302
17	2096	545	1163	428	31	9	266
18	1292	1578	664	990	9	31	397
19	2118	648	1134	452	30	10	339
20	2218	525	1239	375	32	8	288
21	1088	1388	571	110	9	31	256
22	2065	509	1185	379	31	9	255
23	1306	1378	688	959	8	32	319
24	833	1769	426	1176	9	31	305
25	2038	727	1091	498	30	10	342
26	2205	632	1139	456	31	9	335
27	1255	1828	566	1095	9	31	361
28	885	1700	467	1131	9	31	280
29	1572	1068	799	823	9	31	415
30	813	1700	547	1088	9	31	383
31	895	1767	441	1162	9	31	271
<i>Bird 2/2</i>							
1	1337	270	1341	441	33	7	332
2	1241	231	1490	317	33	7	270
3	1147	234	1469	329	32	8	236
4	1014	571	1180	712	7	33	380
5	720	779	867	997	7	33	380
6	886	756	946	854	32	8	399
7	782	1071	745	1093	7	33	399
8	465	1210	539	1282	7	33	255
9	433	1243	454	1339	7	33	232
10	913	814	852	783	31	9	327
11	858	846	778	807	9	31	398
12	1206	889	1038	796	32	8	465
13	644	1018	651	1189	7	33	386
14	968	788	987	770	32	8	445
15	1206	505	1324	520	32	8	337
16	1300	537	1267	548	33	7	325
17	1195	462	1281	536	33	7	322
18	885	930	897	1000	7	33	437
19	1049	728	1053	816	33	7	455
20	1045	509	1145	638	32	8	387
21	788	877	802	1042	7	33	408
22	1050	621	1185	657	33	7	344
23	868	854	879	994	7	33	367
24	481	1151	568	1266	6	34	298
25	850	551	1067	740	32	8	316
26	1141	448	1292	543	32	8	265
27	585	875	713	1112	7	33	256
28	498	790	738	1175	7	33	253
29	453	1089	538	1249	7	33	300
30	350	1139	439	1354	7	33	202
31	447	1275	472	1335	7	33	234

APPENDIX B—continued

Session	Responses		Time (secs)		Reinforcements		Transitions
	Key 1	Key 2	Key 1	Key 2	Key 1	Key 2	Key 1→2
<i>Bird 2/3</i>							
1	1214	535	1221	515	32	8	297
2	1103	476	1272	499	32	8	309
3	1114	308	1283	403	32	8	211
4	944	687	1046	710	8	32	356
5	659	1070	630	1048	9	31	328
6	1086	641	1036	766	33	7	416
7	888	797	833	892	9	31	373
8	864	767	748	997	9	31	435
9	878	940	696	1064	7	33	450
10	1016	800	963	861	31	9	384
11	924	858	830	1047	9	31	393
12	932	776	896	889	32	8	369
13	827	820	682	983	9	31	326
14	1089	886	906	862	33	7	410
15	1145	670	1151	647	32	8	360
16	1166	582	1198	517	32	8	295
17	1118	515	1258	492	32	8	259
18	852	916	879	923	8	32	278
19	941	761	973	779	32	8	300
20	1042	535	1169	576	32	8	256
21	871	750	878	816	9	31	331
22	1004	763	1029	757	32	8	360
23	527	1073	551	1105	8	32	279
24	824	824	815	943	8	32	358
25	853	691	887	923	32	8	347
26	1040	529	1177	640	32	8	259
27	880	854	856	903	8	32	362
28	658	804	633	1022	9	31	313
29	428	1354	381	1296	8	32	194
30	466	1697	328	1448	7	33	178
31	633	1094	478	1228	8	32	280
<i>Bird 2/4</i>							
1	913	437	1291	465	30	10	348
2	1001	494	1250	463	32	8	368
3	965	321	1361	347	32	8	304
4	945	522	1313	577	9	31	428
5	707	792	986	851	8	32	454
6	703	816	923	783	30	10	430
7	707	856	910	970	8	32	431
8	564	948	735	1131	8	32	389
9	684	1120	738	1068	9	31	410
10	772	941	935	928	32	8	148
11	709	950	871	947	7	33	420
12	865	640	1064	636	31	9	401
13	700	776	921	921	9	31	342
14	919	591	1178	623	31	9	362
15	901	474	1222	473	31	9	319
16	1024	376	1323	377	32	8	265
17	1019	371	1310	378	32	8	270
18	697	773	950	887	9	31	386
19	701	656	1059	730	31	9	366
20	897	462	1208	478	32	8	328
21	764	690	1038	795	9	31	454
22	746	651	1002	674	31	9	371
23	698	849	920	939	9	31	435
24	669	895	851	951	9	31	385
25	746	597	984	666	30	10	350
26	951	413	1234	440	31	9	314
27	729	769	946	855	9	31	360
28	474	802	776	1031	8	32	317
29	463	969	660	1160	9	31	334
30	548	834	685	1010	10	30	294
31	440	960	611	1191	9	31	—

APPENDIX B—continued

Session	Responses		Time (secs)		Reinforcements		Transitions
	Key 1	Key 2	Key 1	Key 2	Key 1	Key 2	Key 1→2
<i>Bird 2/5</i>							
1	1394	577	1352	500	33	7	284
2	1310	643	1380	500	32	8	291
3	1285	547	1422	482	33	7	280
4	1076	665	1265	627	9	31	330
5	757	745	1114	760	8	32	361
6	1074	834	1124	708	32	8	374
7	723	888	954	924	8	32	301
8	793	1130	879	1011	8	32	365
9	620	914	938	1027	7	33	256
10	670	984	881	916	32	8	335
11	818	991	948	831	8	32	403
12	1123	910	1093	789	33	7	406
13	937	782	1090	783	7	33	380
14	1006	867	1056	792	32	8	366
15	933	749	1152	715	32	8	314
16	656	545	1231	695	32	8	247
17	992	619	1289	631	31	9	303
18	854	747	1066	875	8	32	404
19	827	730	1121	757	33	7	382
20	1016	632	1242	626	32	8	307
21	953	758	1107	790	7	33	368
22	797	645	1157	728	32	8	338
23	748	874	908	938	7	33	471
24	768	889	933	982	7	33	374
25	730	927	916	965	33	7	430
26	941	745	1142	697	32	8	357
27	912	905	988	925	7	33	450
28	556	790	881	979	8	32	402
29	679	933	864	992	7	33	339
30	562	821	915	1047	6	34	304
31	457	848	721	1163	7	33	275
<i>Bird 2/6</i>							
1	803	196	1359	443	32	8	271
2	1008	241	1315	438	32	8	249
3	1070	225	1336	349	31	9	196
4	757	427	1056	858	7	33	289
5	550	503	784	1063	8	32	335
6	589	424	848	963	32	8	347
7	542	425	728	1041	8	32	355
8	520	419	821	953	7	33	405
9	429	471	692	1065	9	31	372
10	620	466	954	907	31	9	384
11	773	558	865	966	10	30	392
12	977	430	1030	749	32	8	448
13	595	430	821	930	9	31	385
14	656	517	811	1014	33	7	419
15	1020	382	1228	592	32	8	451
16	991	388	1203	591	32	8	505
17	1075	420	1177	579	31	9	501
18	682	460	969	860	7	33	418
19	560	391	983	709	31	9	338
20	492	191	1266	534	32	8	279
21	434	374	875	926	8	32	305
22	459	345	1082	777	33	7	369
23	335	357	686	1086	8	32	245
24	324	394	628	1095	9	31	290
25	309	181	1055	779	32	8	256
26	537	157	1270	541	33	7	261
27	430	331	806	982	9	31	294
28	176	242	635	1132	8	32	167
29	273	379	562	1109	9	31	202
30	362	369	633	1167	8	32	278
31	436	496	602	1093	9	31	338