

*CONCURRENT SCHEDULES: INTERACTION OF REINFORCER  
FREQUENCY AND REINFORCER DURATION*

MICHAEL DAVISON

UNIVERSITY OF AUCKLAND, NEW ZEALAND

Six pigeons were trained on concurrent variable-interval schedules with unequal reinforcer durations for the two responses. The schedules arranged on the two keys were kept equal while they were varied in absolute size. As the overall reinforcer rate was increased, both response-allocation and time-allocation measures of choice showed a trend toward indifference, and measures of sensitivity to reinforcer-duration ratios significantly decreased. Recent reports have shown that the generalized matching law cannot describe the changes in behavior allocation under constant delay-, duration-, or rate-ratios when changes are made in the absolute levels of each of these variables. The present results complement these findings by demonstrating that the concatenated generalized matching law cannot describe the interactions of two reinforcer variables on behavior allocation.

*Key words:* concurrent schedules, reinforcer frequency, reinforcer duration, generalized matching, preference, key peck, pigeons

Initial results from the study of how variations in reinforcer duration affected responding on concurrent variable-interval (VI) schedules indicated that the ratio of responses emitted on the two schedules equaled the ratio of reinforcer durations provided (Catania, 1963; Neuringer, 1967). Using the generalized matching equation (Baum, 1974), with  $B$  denoting responses and  $M$  denoting reinforcer magnitudes (or durations, or amounts), these results can be written:

$$\log\left(\frac{B_1}{B_2}\right) = a_m \log\left(\frac{M_1}{M_2}\right) + \log c. \quad (1)$$

In this equation, the subscripts indicate the two schedules. The parameter  $a_m$  is called sensitivity to reinforcement (Lobb & Davison, 1975), and it measures the rate of change of the log behavior ratio with changes in the log reinforcer-magnitude ratio. The second parameter,  $\log c$ , is called bias, and it measures a constant proportional preference for one alternative over the other that is maintained when the independent variable (here,  $\log M_1/M_2$ ) is

manipulated. The equality between response ratios and reinforcer-duration ratios found by Catania and by Neuringer implies that  $a_m = 1$  and  $\log c = 0$  in Equation 1. This finding was confirmed by Brownstein (1971) using time-allocation ( $\log T_1/T_2$ ) measures rather than response-allocation measures.

Subsequent, and more extensive, work (Fantino, Squires, Delbrück, & Peterson, 1972; Schneider, 1973; Todorov, 1973; see also Davison & McCarthy, 1988) failed to support the initial finding that subjects strictly matched behavior-output ratios to reinforcer-magnitude (or -amount) input ratios. Rather, behavior-output ratios undermatched reinforcer-magnitude input ratios, implying that  $a_m$  in Equation 1 was less than 1. Two of these studies (Schneider, Todorov) also varied reinforcer-frequency ratios. Using Equation 2:

$$\log\left(\frac{B_1}{B_2}\right) = a_m \log\left(\frac{M_1}{M_2}\right) + a_r \log\left(\frac{R_1}{R_2}\right) + \log c, \quad (2)$$

they also found that sensitivity to reinforcer magnitude ( $a_m$ ) was usually less than sensitivity to reinforcer frequency ( $a_r$ ). A similar result was obtained in the reanalysis of Fantino et al.'s (1972) data done by Davison and McCarthy. These results suggest that the generalized matching law is a reasonable description of behavior allocation under varying frequencies and magnitudes of reinforcers, but that

I thank the New Zealand University Grants Committee and the Auckland University Research Committee for numerous equipment grants, the staff, Masters and Doctoral students who helped conduct this experiment, and Dianne McCarthy for commenting on a version of this paper. Reprints may be obtained from Michael Davison, Psychology Department, University of Auckland, Private Bag, Auckland, New Zealand.

the value of the sensitivity parameter depends on the type of independent variable manipulated.

A further result reported by Davison and Hogsden (1984) cast doubt on the ability of the generalized matching law to describe effects of reinforcer magnitude on concurrent-schedule performance. In Part 5 of their experiment, they arranged a 3-s reinforcer on one key and varied the reinforcer duration on the other key from 1 s to 10 s. A plot of log response ratios against log reinforcer-duration ratios (their Figure 5) was clearly nonlinear, implying that  $a_m$  was not a constant but rather depended on the absolute value of the durations.

In related research, Williams and Fantino (1978) showed that sensitivity to the delay ratio increased with the size of the delay ratio (see their reanalysis of Chung & Herrnstein's [1967] data; see also Davison & Temple [1973] and Duncan & Fantino [1970]). In a design in which one delay was kept constant and the other, larger, delay was varied, sensitivity to delay progressively changed (Davison & Temple, 1973).

Similar problems with reinforcer magnitude and delay, and an additional problem with reinforcer rate, were clearly shown in research reported by Logue and Chavarro (1987). In Experiment 1, pigeons worked on concurrent VI 8-s VI 8-s schedules with a delay ratio of 3:1, and the absolute duration of the delays was varied. Preference increased as the absolute delays were made longer (the standard concurrent-chain result; Duncan & Fantino, 1970). In Experiment 2, the reinforcer-duration ratio was set at 3:1 on concurrent VI 8-s VI 8-s schedules with 6-s reinforcer delays on both keys. Preference increased as the absolute durations were made smaller. In Experiment 3, the reinforcer-frequency ratio was set at 3:1 and both reinforcer durations and delays were set at 6 s. Preference increased as the reinforcer frequency was increased. As Logue and Chavarro concluded, the generalized matching law (with constant parameters) cannot describe these trends.

The above results all indicate that the generalized matching law has serious problems in describing changes in preference for an independent variable when that variable is changed. Data have also been reported implying that there are *interactions* between independent

variables that cannot be described by the generalized matching law. It is well known that sensitivity to delay ratios is affected by the overall frequency of presentation of the delays. Sensitivity is high when they occur frequently (i.e., when response allocation is measured during concurrent high-rate VI schedules) and falls with decreasing frequencies of delay presentation (Davison, 1983, 1987; Fantino, 1969; Fantino & Davison, 1983; Squires & Fantino, 1971).

The present experiment asked simply whether a similar interaction occurred in the control of preference by reinforcer rate and reinforcer duration. On concurrent schedules with constant, but different, reinforcer durations, would response allocation and/or time allocation change if the two schedules were kept equal, but the overall frequency of reinforcement was varied?

## METHOD

### *Subjects*

Six homing pigeons, numbered 21 to 26, were maintained at 85% of their free-feeding body weights by feeding varying amounts of mixed grain immediately after the daily training sessions. The subjects had previously been used by Davison and Hogsden (1984).

### *Apparatus*

The apparatus was that used by Davison and Hogsden (1984). The sound-attenuated experimental chamber, in which noise was masked by an exhaust fan, was situated remote from solid-state programming equipment. The dimensions of the chamber were 35 cm high by 30 cm wide by 35 cm deep. Two response keys, which were 2 cm in diameter and required about 0.1 N for their operation, were situated on one wall of the chamber. They were 11 cm apart and 25 cm from the grid floor. A food hopper containing wheat was situated midway between the keys and 10 cm from the floor. Reinforcement consisted of raising the hopper and illuminating the wheat for fixed periods of time. The keylights were extinguished during reinforcement. There was no houselight or any illumination in the chamber except the key and magazine lights. Effective responses on the lighted keys were counted and were followed by feedback clicks.

### Procedure

Experimental sessions were conducted 7 days per week. They commenced in blackout and ended in blackout after a fixed number of reinforcers had been obtained or after 45 min had elapsed, whichever event occurred first. Each experimental condition was in effect until a stability criterion had been met, at which point the condition was changed for all subjects. The initial criterion was that the median relative response rate on the left key over five sessions was not more than .05 different from the median over the immediately preceding five sessions. This criterion had to be met five, not necessarily consecutive, times for all 6 subjects before experimental conditions were changed. These criteria thus define a minimum of 14 sessions per condition. The actual number of sessions arranged in each condition is shown in Table 1.

Experimental sessions began with both keys lit white. Responses on the two keys were reinforced on concurrent arithmetic VI VI schedules. Each schedule consisted of a set of 12 intervals arranged in an irregular order, with the smallest interreinforcement interval one twelfth the mean interval. The concurrent schedules were arranged nonindependently (Stubbs & Pliskoff, 1969). A single timer arranged each interval to reinforcement, and when it had completed timing, the reinforcer was allocated by a probability gate set at .5 to one of the two keys. When a reinforcer was arranged by one schedule, the other schedule stopped timing until that reinforcer had been collected. Then, when reinforcer delivery ended, both schedules continued timing. A changeover delay (Herrnstein, 1961) was also used so that a reinforcer, if arranged by a schedule, could not be obtained until 3 s after the subject commenced responding on that key after responding on the other key.

The sequence of experimental conditions is shown in Table 1 with the number of training sessions arranged on each condition. Because the subjects had extensive training on similar experimental conditions in the same chamber (Davison & Hogsden, 1984, and similar subsequent conditions), no preliminary training was necessary, and the subjects were placed directly on Condition 1. The design of the experiment was first to arrange 10-s reinforcers for responding on the left key and 3-s rein-

Table 1

Sequence of experimental sessions, base VI schedule (with reinforcers allocated with  $p = .5$ ), reinforcer durations, and number of sessions arranged per condition. Schedule and reinforcer-duration values are in seconds.

Con- dition	Schedule	Reinforcer duration		Sessions
		Left	Right	
1	120	10	3	30
2	30	10	3	26
3	60	10	3	23
4	120	10	3	35
5	180	10	3	23
6	240	10	3	28
7	240	3	10	25
8	30	3	10	35
9	16	3	10	24
10	16	10	3	27

forcers for responding on the right key, and to increase over conditions the length of the equal VI schedules from concurrent VI 60 s VI 60 s (i.e., a VI 30-s schedule with reinforcers allocated with  $p = .5$ ; Table 1) to concurrent VI 480 s VI 480 s. Then, in Condition 7, the reinforcer durations were reversed, keeping the same schedules as in Condition 6. In Condition 8, the schedules were changed to concurrent VI 60 s VI 60 s, and in Condition 9 to concurrent VI 32 s VI 32 s. Finally, in Condition 10, an additional reversal in reinforcer durations was carried out.

## RESULTS

The numbers of responses emitted, the time in minutes spent responding, and the number of reinforcers obtained, each summed over the final five sessions of each experimental condition, are shown in the Appendix. Approximately equal numbers of reinforcers were obtained on each key, as arranged by the dependent-scheduling procedure. However, because the reinforcers were allocated using a probability gate, occasionally the reinforcers obtained were not equal (e.g., Bird 22, Conditions 1, 3, and 8). We will return to this problem later. Responses emitted and times spent responding varied considerably for some subjects (see, for instance, Bird 21, Conditions 2 to 6).

The changes in individual-subject response allocation to the two schedules as a function of overall obtained reinforcer rate are shown

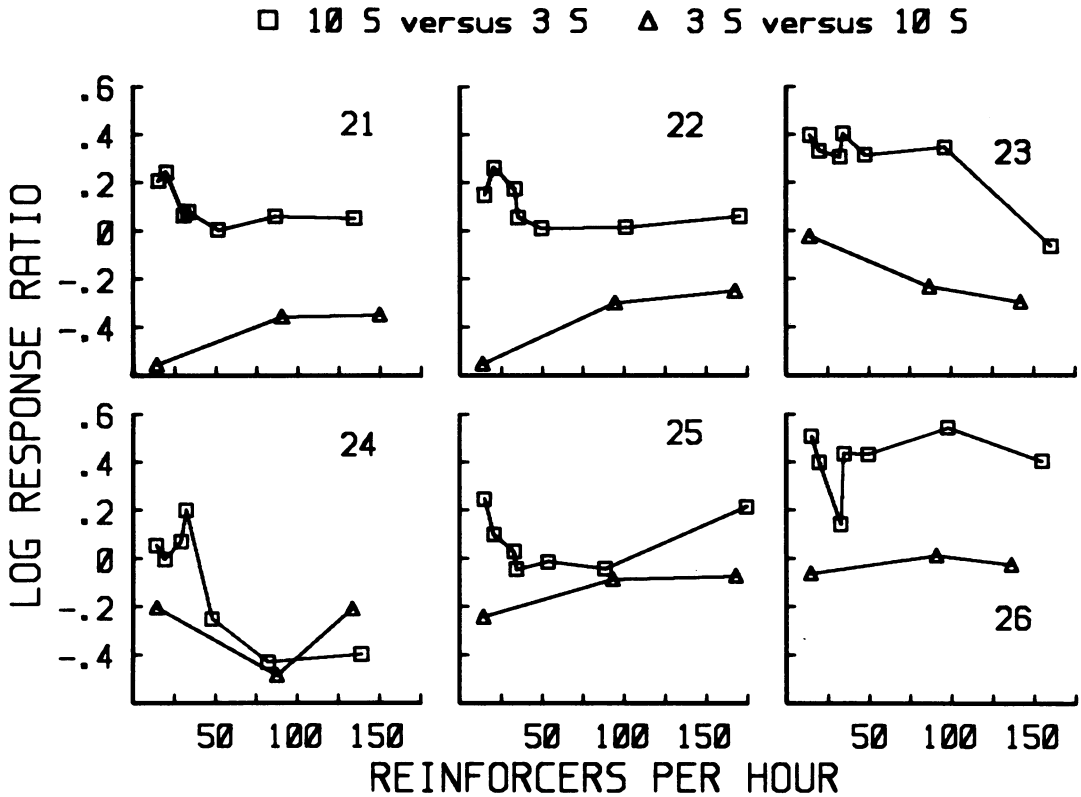


Fig. 1. Log response-rate ratios (left key over right key) as a function of the overall number of reinforcers obtained per hour. The data for each individual subject are shown. The data from the 10-s (left key) versus 3-s (right key) reinforcer duration conditions, and those from the reversal of these durations, are shown separately.

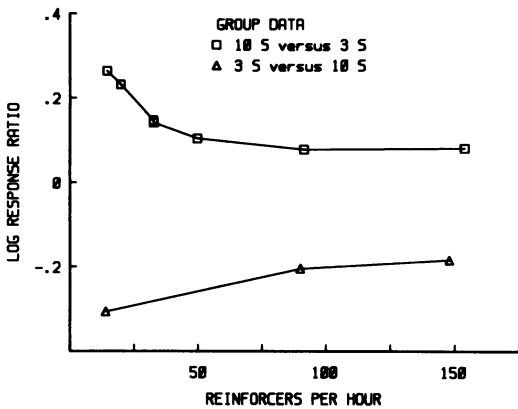


Fig. 2. Group average log response-rate ratios (left key over right key) as a function of the overall average numbers of reinforcers per hour. The data from the 10-s (left key) versus 3-s (right key) reinforcer duration conditions, and those from the reversal of these durations, are shown separately.

in Figure 1. In this and subsequent figures, log left-key over right-key response (or time) ratios are shown as a function of the number of reinforcers obtained per hour. Preference for the 10-s (left) over the 3-s (right) reinforcer (Conditions 1 to 6 and 10) moved towards the value of preference for the 3-s reinforcer over the 10-s reinforcer (Conditions 7 to 9) as the overall reinforcer rate was increased. A non-parametric test of the trends shown in Figure 1 (Ferguson, 1965) gave the following results: On a nondirectional test, the decreasing trends in the 10-s (left) versus 3-s (right) reinforcer-duration data were significant at beyond the  $p = .01$  criterion ( $z = 2.76$ , with  $N = 6$  subjects and  $k = 7$  conditions). For the three conditions in which the preference was between 3-s (left) and 10-s (right) reinforcers, a significant trend was not obtained. These trends are more easily seen in the group data shown in Figure 2, in which the preferences change strictly mono-

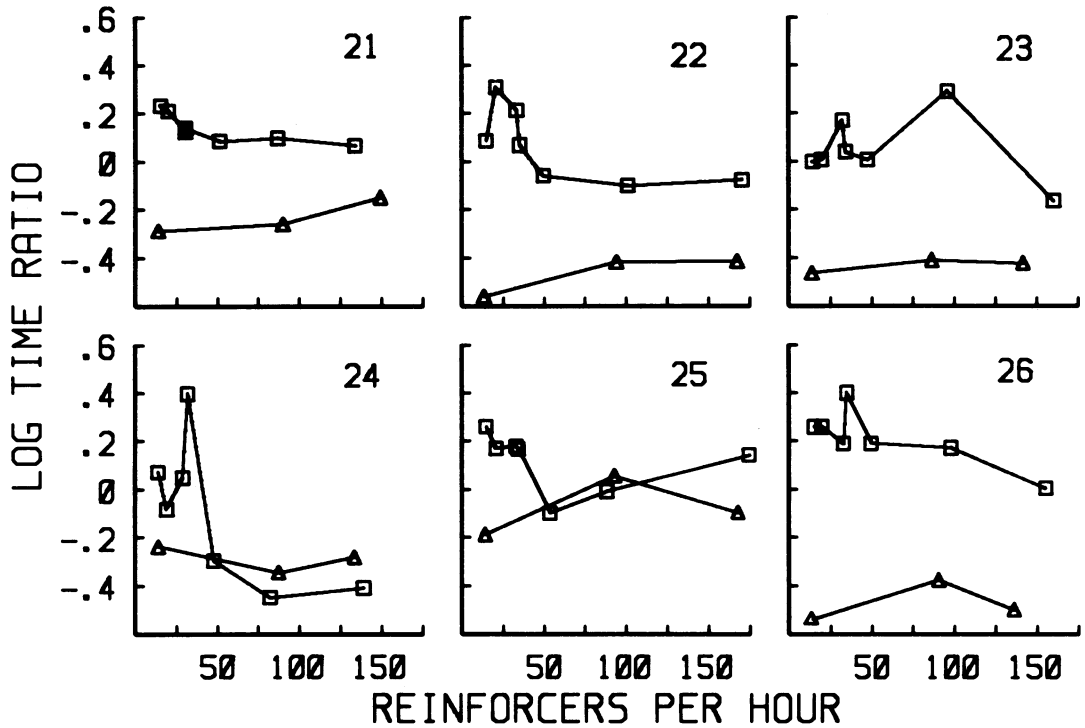


Fig. 3. Log time-allocation ratios (left key over right key) as a function of the overall number of reinforcers obtained per hour. The data for each individual subject are shown. The data from the 10-s (left key) versus 3-s (right key) reinforcer duration conditions, and those from the reversal of these durations, are shown separately.

tonically. The performance of Bird 24 (Figure 1) was clearly biased towards the right key with a value of  $\log c$  in Equations 1 and 2 of about  $-0.4$ . The performance of Bird 26 seemed to be biased to the left key.

Figures 3 and 4 are similar to Figures 1 and 2, but they show time-allocation data. Again, the log response ratios for the 10-s (left) versus 3-s (right) durations moved towards the measures for the 3-s (left) versus 10-s (right) durations as the overall reinforcer rate was increased. A nonparametric test of the trends shown in Figure 3 (Ferguson, 1965) gave the following results: On a nondirectional test, the decreasing trends in the 10-s (left) versus 3-s (right) reinforcer-duration data were significant at beyond the  $p = .01$  criterion ( $z = 4.29$ , with  $N = 6$  subjects and  $k = 7$  conditions). For the three conditions in which the preference was between 3-s (left) and 10-s (right) reinforcers, a significant trend was not obtained. Again, the trends are more easily seen in the group data shown in Figure 4. The response-allocation bias noted above for Bird 24 is paralleled by a similar time-allocation

bias (Figure 3), but the time bias for Bird 26 seems to be toward the right key.

It can be seen from Figures 1 to 4 that the data obtained from Conditions 1 and 4 (both

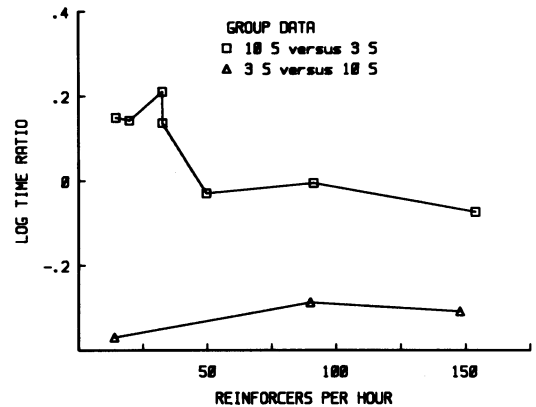


Fig. 4. Group average log time-allocation ratios (left key over right key) as a function of the overall average numbers of reinforcers per hour. The data from the 10-s (left key) versus 3-s (right key) reinforcer duration conditions, and those from the reversal of these durations, are shown separately.

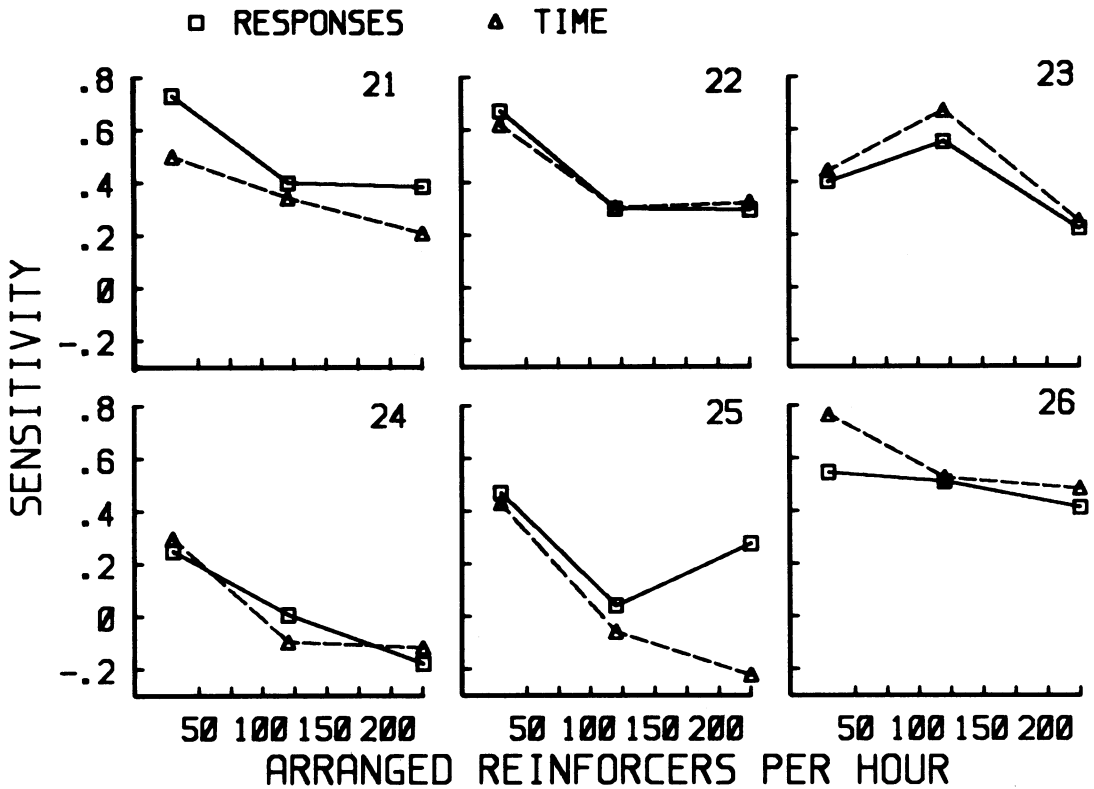


Fig. 5. Response- and time-allocation measures of sensitivity to reinforcer duration ( $a_m$ , Equation 1) as a function of the overall arranged reinforcers per hour for each individual subject.

concurrent VI 240 s VI 240 s, about 30 reinforcers obtained per hour) were generally similar. However, poor replications are evident for Bird 26 (response measures) and Bird 24 (time measures).

A further analysis of the trends in the present data was carried out, taking into account the deviations from equal reinforcer frequencies for the two responses (see Appendix). This was done by assuming  $a_r = 1$  in Equation 2, and subtracting  $\log(R_1/R_2)$  from the log behavior-ratio measure. Again, on a nondirectional test, the decreasing trends in the 10-s (left) versus 3-s (right) data were significant (responses,  $z = 2.33$ ,  $p < .05$ ; time,  $z = 2.70$ ,  $p < .01$ ). The trends in the 3-s (left) versus 10-s (right) data remained nonsignificant. It therefore appears that removing the differences in reinforcer frequencies produced by sampling error probably only increased the error variance in the log behavior-ratio measures.

For three overall reinforcer rates (VI 16 s,

VI 30 s, VI 240 s), the subjects were exposed to both 10-s (left) versus 3-s (right) reinforcers and to 3-s (left) versus 10-s (right) reinforcers. Differences between the pairs of measures from these three conditions showed a significant decreasing trend with increasing reinforcer rates (nondirectional nonparametric trend test,  $z = 2.56$  and  $2.34$ ,  $p < .05$ , for response and time measures, respectively). From such reversals,  $a_m$  in Equation 2 can be calculated directly under the assumption that the obtained overall reinforcer rates in each condition and its reversal were similar. Figures 1 and 3 show that this assumption was met at least at the two lower reinforcer rates. At the highest reinforcer rate (Conditions 9 and 10), there were some differences in overall reinforcer rate, but these were in no consistent direction. The results of these calculations are shown in Figure 5 plotted as a function of the *arranged* overall reinforcer rate. For 4 of the 6 birds, response-measured sensitivity fell monotonically with increasing overall reinforcer rate, and for 5 of

the 6 birds time-measured sensitivity fell monotonically. Nonparametric trend tests showed that both trends were significant at  $p < .01$  (both  $z = 2.98$ , nondirectional tests).

## DISCUSSION

The results of the present experiment show that concurrent-schedule preference between different reinforcer durations may not be independent of the overall frequency with which the reinforcers are produced. Rather, both response and time allocation to the two schedules showed a tendency to become less extreme as the frequency with which the reinforcers were produced was increased. In terms of the generalized matching law (Equation 1),  $a_m$  fell significantly as overall reinforcer rate was increased. Because Conditions 2 to 6 arranged progressively decreasing reinforcer rates, it could be argued that the results for the 10-s versus 3-s reinforcer durations could have been simply an artifact of the sequence arranged. The argument against this is that Conditions 7 to 9 arranged increasing reinforcer rates, but the mirror-image trend (admittedly nonsignificant) was obtained. Further, sensitivity to reinforcement measures, which used both ascending and descending reinforcer-rate conditions, showed a significant trend (for both response and time measures) in the three pairs of overall reinforcer-rate conditions in which the reinforcer durations were reversed.

Before discussing the implications of the present results, it is necessary to acknowledge that there are two possible explanations (suggested by reviewers of this paper) for the reported decrease in preference between reinforcer durations with increasing reinforcer rates. Both suggest that the controlling variable is not overall reinforcer rate per se, but rather an interaction of this variable with a third variable. The first possible explanation is that, because the changeover delay (COD) was kept constant as the overall reinforcer rate increased, switching rate increased and inter-changeover times on both keys decreased toward an asymptotic value of about 3 s (the COD duration), leading to indifference in behavior allocation. As Alsop and Elliffe (1988) showed, changeover rates do increase with overall reinforcer rates. But they also showed that, in concurrent VI VI schedules, this was associated with an increase in the control by

reinforcer-rate differentials, rather than the decrease predicted by this explanation. Given that this first explanation does not address the reinforcer-duration differentials used here, it can be ruled out. Indeed, because the effect found here was opposite in direction to that found by Alsop and Elliffe, the current finding is strengthened. For example, under this hypothesis, a directional (rather than nondirectional) test for trend could have been carried out.

The second possible explanation concerns an effect of increasing reinforcer rates on the amount eaten during reinforcer delivery. Epstein (1981) reported that the amount consumed by pigeons during a magazine-presentation cycle was a negatively accelerated function of magazine-cycle duration. Because the magazine used here did not allow refilling during its presentation, according to Epstein's function the amount-consumed ratio for 10-s versus 3-s durations would be about 3:2 (a log value of 0.18). On the average (Figure 2), preference at low reinforcer rates exceeded this value. The hypothesis suggests that, at high overall reinforcer rates, subjects will consume proportionally less per presentation of the longer versus the shorter duration. There seem to be no published data that directly support or refute this suggestion. Because sessions ended here either after an elapsed time or after a fixed number of reinforcers, postfeed records do not provide useful information. This hypothesis, however, suggests the following result: If a constant overall reinforcer rate is maintained, and reinforcer durations are varied, a plot of the log preference ratio against the log arranged reinforcer-duration ratio would produce a concave downward function when the duration ratio was increased from 1.0. The direction of curvature of this function is in the opposite direction to that empirically determined by Davison and Hogsden (1984). Thus, this explanation can probably be ruled out for the effect reported here.

Previous research has shown that the generalized matching law cannot describe the effects of varying the absolute levels of choice-affecting variables on preference (e.g., Logue & Chavarro, 1987). With the caveat above, the present research has shown that the same law cannot describe the interaction of two choice-affecting variables on behavior allocation. The latter conclusion is supported both

by the present data (reinforcer frequency and duration interactions) and by previous data on the effects of overall reinforcer frequency on preference between reinforcer delays (e.g., Davison, 1987; Fantino, 1969; Fantino & Davison, 1983; Squires & Fantino, 1971). These results taken together have fundamental implications for both the form of equations relating single-variable manipulations to behavior allocation and for the way in which such equations are to be concatenated to describe behavior allocation as a function of more than one variable.

The generalized matching law, as a *formal* relation (McDowell, 1986), could be sustained if it were allowed that the measure of sensitivity to reinforcement ( $a$ ) were a variable rather than a constant. Thus,  $a_m$  (Equation 2) would be a function of both absolute reinforcer durations (Davison & Hogsden, 1984) and overall reinforcer frequencies. But, because the goal of a quantitative analysis of behavior must be to discover invariances in behavior (Nevin, 1984), firstly as invariant data and then as invariant derived measures, such a move would be retrograde. In the light of the present data and those of Logue and Chavarro (1987), we must look elsewhere for a model of reinforcer-frequency versus reinforcer-duration interactions on behavior, as we must do also for reinforcer-frequency and reinforcer-delay interactions (Davison, 1987). The present results thus also call into doubt any attempt to describe the interaction of reinforcer delay and duration using the generalized matching law with constant parameters (e.g., in the study of "self-control"; Snyderman, 1983). It is worth recalling, though, that there is one combination of choice-affecting variables that is well described by the concatenated generalized matching law—reinforcer rate and response force (Hunter & Davison, 1982). It may be significant that this is a reinforcer–response independent-variable combination, rather than a combination of two aspects of reinforcers.

What alternative to the generalized matching law might describe the preference changes found in the present experiment? One obvious candidate is the delay-reduction hypothesis (Fantino, 1969; Fantino & Davison, 1983; Navarick & Fantino, 1976; Squires & Fantino, 1971). However, the extension of this model to the combination of reinforcer rates

and durations was shown by Snyderman (1983) to be unable to describe some conditions of his data and some of those reported by Green and Snyderman (1980). Logue and Chavarro (1987) found that the delay-reduction model could not accurately describe the results from any of their three experiments. Modifications of the delay-reduction model (Green & Snyderman, 1980; Ito & Asaki, 1982) were also discussed by Snyderman and found wanting. The main problem for these models, and for that offered by Killeen (1982), is Snyderman's finding that preference for 6-s versus 2-s reinforcers increased as the equal times in the terminal links of the concurrent-chain schedules was increased. Although Killeen (1985) showed how incentive theory could accommodate the major trends in Snyderman's data, this theory cannot, as it stands, account for the present data. Because, according to Killeen, directive strength,  $S$ , is a multiplicative function of rate of incitement,  $R$ , and directive effect,  $S_d$ , and because the value of the directive effect was kept constant here within the 10-s (left) versus 3-s (right) and 3-s (left) versus 10-s (right) conditions, incentive theory predicts at worst no reinforcer rate–duration interactions or, at best, a very minor interaction due to the latency of eating at the hopper. Similarly, incentive theory cannot describe changes in sensitivity to relative reinforcer rate as a function of overall reinforcer rate when no reinforcer delays are arranged (Alsop & Elliffe, 1988). Of course, if incentive theory assumed that the value of a reinforcer were an inverse function of its frequency, it would have no problem with these results.

A quantitative model of the joint effects of reinforcer durations and magnitudes on behavior allocation in concurrent VI VI schedules should have the following properties. Using  $a_r$  and  $a_m$  to denote the sensitivities of behavior allocation to reinforcer frequency and duration, respectively, simply as measures without any commitment to Equation 2, the following results have been obtained: (a)  $a_r$  increases with overall reinforcer rates if no delays to reinforcers are arranged (Alsop & Elliffe, 1988) or if 6-s delays are arranged (Logue & Chavarro, 1987), and, in both cases, changeover delays are used. However, if 20-s delays are arranged,  $a_r$  falls as reinforcer rate is increased (see Conditions 46, 47, 53, and 54



of Fantino & Davison, 1983). Indeed, the general concurrent-chain result is that increasing terminal links decrease control by differential initial links (Davison, 1987). But the difficulty of many of these results is that changeover delays were not used and that  $a_r$  values were not obtained using a constant overall reinforcer rate (i.e., one schedule was kept constant while the other was varied). Both of these variables could be critical. (b) There seems to be no published information as to whether  $a_r$  changes with total reinforcer duration.

Sensitivity to relative reinforcer duration,  $a_m$ , decreases with increasing reinforcer durations (Logue & Chavarro, 1987), at least when a changeover delay and 6-s reinforcer delays are arranged, and also falls as total reinforcer rate is increased (the present result, using a changeover delay and no reinforcer delays).

In terms of model building the situation is confusing, and it is confused further by the finding (Davison & Hogsden, 1984) that the relation between log response-allocation ratios and log reinforcer-duration ratios may be nonlinear (concave upward) when relative and overall total durations are positively correlated. This finding seems to be inconsistent with the Logue and Chavarro (1987) result mentioned above. But it is consistent with research on reinforcer immediacy (i.e., the reciprocal of delay). Sensitivity to reinforcer immediacy decreases with increased immediacy (Logue & Chavarro, 1987; MacEwen, 1972), and the relation between log response-allocation ratios and log immediacy ratios is nonlinear when relative and total immediacies are correlated (Davison & Temple, 1973).

No obvious candidate for a quantitative model of reinforcer-rate and reinforcer-duration interaction is implied by the available data. Indeed, data to guide the development of such a model are in some cases absent, and in other cases may be confounded with other variables (e.g., the effects of reinforcer delay and changeover delay on the relation between  $a_r$  and total reinforcer rate). Rather than speculation about models, what is required now is a considerable amount of empirical research to chart in a more detailed fashion the effects of relative and overall reinforcer rates and reinforcer durations, and the interactions between these in their effects on choice.

## REFERENCES

- Alsop, B., & Elliffe, D. (1988). Concurrent-schedule performance: Effects of relative and overall reinforcer rate. *Journal of the Experimental Analysis of Behavior*, **49**, 21-36.
- Baum, W. M. (1974). On two types of deviation from the matching law: Bias and undermatching. *Journal of the Experimental Analysis of Behavior*, **22**, 231-242.
- Brownstein, A. J. (1971). Concurrent schedules of response-independent reinforcement: Duration of a reinforcing stimulus. *Journal of the Experimental Analysis of Behavior*, **15**, 211-214.
- Catania, A. C. (1963). Concurrent performances: A baseline for the study of reinforcement magnitude. *Journal of the Experimental Analysis of Behavior*, **6**, 299-300.
- Chung, S.-H., & Herrnstein, R. J. (1967). Choice and delay of reinforcement. *Journal of the Experimental Analysis of Behavior*, **10**, 67-74.
- Davison, M. (1983). Bias and sensitivity to reinforcement in a concurrent-chain schedule. *Journal of the Experimental Analysis of Behavior*, **40**, 15-34.
- Davison, M. (1987). The analysis of concurrent-chain performance. In M. L. Commons, J. E. Mazur, J. A. Nevin, & H. Rachlin (Eds.), *Quantitative analyses of behavior: Vol. 5. The effect of delay and of intervening events on reinforcement value* (pp. 225-241). Hillsdale, NJ: Erlbaum.
- Davison, M., & Hogsden, I. (1984). Concurrent variable-interval schedule performance: Fixed versus mixed reinforcer durations. *Journal of the Experimental Analysis of Behavior*, **41**, 169-182.
- Davison, M., & McCarthy, D. (1988). *The matching law: A research review*. Hillsdale, NJ: Erlbaum.
- Davison, M. C., & Temple, W. (1973). Preference for fixed-interval schedules: An alternative model. *Journal of the Experimental Analysis of Behavior*, **20**, 393-403.
- Duncan, B., & Fantino, E. (1970). Choice for periodic schedules of reinforcement. *Journal of the Experimental Analysis of Behavior*, **14**, 73-86.
- Epstein, R. (1981). Amount consumed as a function of magazine-cycle duration. *Behaviour Analysis Letters*, **1**, 63-66.
- Fantino, E. (1969). Choice and rate of reinforcement. *Journal of the Experimental Analysis of Behavior*, **12**, 723-730.
- Fantino, E., & Davison, M. (1983). Choice: Some quantitative relations. *Journal of the Experimental Analysis of Behavior*, **40**, 1-13.
- Fantino, E., Squires, N., Delbrück, N., & Peterson, C. (1972). Choice behavior and the accessibility of the reinforcer. *Journal of the Experimental Analysis of Behavior*, **18**, 35-43.
- Ferguson, G. A. (1965). *Nonparametric trend analysis*. Montreal: McGill University Press.
- Green, L., & Snyderman, M. (1980). Choice between rewards differing in amount and delay: Toward a choice model of self control. *Journal of the Experimental Analysis of Behavior*, **34**, 135-147.
- Herrnstein, R. J. (1961). Relative and absolute strength of response as a function of frequency of reinforcement. *Journal of the Experimental Analysis of Behavior*, **4**, 267-272.

- Hunter, I., & Davison, M. (1982). Independence of response force and reinforcement rate on concurrent variable-interval schedule performance. *Journal of the Experimental Analysis of Behavior*, *37*, 183-197.
- Ito, M., & Asaki, K. (1982). Choice behavior of rats in a concurrent-chains schedule: Amount and delay of reinforcement. *Journal of the Experimental Analysis of Behavior*, *37*, 383-392.
- Killeen, P. R. (1982). Incentive theory: II. Models for choice. *Journal of the Experimental Analysis of Behavior*, *38*, 217-232.
- Killeen, P. R. (1985). Incentive theory: IV. Magnitude of reward. *Journal of the Experimental Analysis of Behavior*, *43*, 407-417.
- Lobb, B., & Davison, M. C. (1975). Performance in concurrent interval schedules: A systematic replication. *Journal of the Experimental Analysis of Behavior*, *24*, 191-197.
- Logue, A. W., & Chavarro, A. (1987). Effect on choice of absolute and relative values of reinforcer delay, amount, and frequency. *Journal of Experimental Psychology: Animal Behavior Processes*, *13*, 280-291.
- MacEwen, D. (1972). The effects of terminal-link fixed-interval and variable-interval schedules on responding under concurrent chained schedules. *Journal of the Experimental Analysis of Behavior*, *18*, 253-261.
- McDowell, J. J. (1986). On the falsifiability of matching theory. *Journal of the Experimental Analysis of Behavior*, *45*, 63-74.
- Navarick, D. J., & Fantino, E. (1976). Self-control and general models of choice. *Journal of Experimental Psychology: Animal Behavior Processes*, *2*, 75-87.
- Neuringer, A. J. (1967). Effects of reinforcement magnitude on choice and rate of responding. *Journal of the Experimental Analysis of Behavior*, *10*, 417-424.
- Nevin, J. A. (1984). Quantitative analysis. *Journal of the Experimental Analysis of Behavior*, *42*, 421-434.
- Schneider, J. W. (1973). Reinforcer effectiveness as a function of reinforcer rate and magnitude: A comparison of concurrent performances. *Journal of the Experimental Analysis of Behavior*, *20*, 461-471.
- Snyderman, M. (1983). Delay and amount of reward in a concurrent chain. *Journal of the Experimental Analysis of Behavior*, *39*, 437-447.
- Squires, N., & Fantino, E. (1971). A model for choice in simple concurrent and concurrent-chains schedules. *Journal of the Experimental Analysis of Behavior*, *15*, 27-38.
- Stubbs, D. A., & Pliskoff, S. S. (1969). Concurrent responding with fixed relative rate of reinforcement. *Journal of the Experimental Analysis of Behavior*, *12*, 887-895.
- Todorov, J. C. (1973). Interaction of frequency and magnitude of reinforcement on concurrent performances. *Journal of the Experimental Analysis of Behavior*, *19*, 451-458.
- Williams, B. A., & Fantino, E. (1978). Effects on choice of reinforcement delay and conditioned reinforcement. *Journal of the Experimental Analysis of Behavior*, *29*, 77-86.

Received August 25, 1987

Final acceptance January 17, 1988

## APPENDIX

Number of responses emitted, minutes spent responding, and number of reinforcers obtained, on each key summed over the last five sessions of each experimental condition.

Condition	Responses		Minutes		Reinforcers	
	Left	Right	Left	Right	Left	Right
Bird 21						
1	7,141	5,952	128.58	96.40	65	59
2	1,952	1,697	38.52	30.76	50	50
3	3,666	3,644	64.34	52.90	44	56
4	7,688	6,644	115.48	83.64	52	48
5	9,835	5,593	140.78	86.40	38	36
6	8,984	5,570	143.58	83.76	31	25
7	4,268	15,357	77.98	151.40	26	28
8	1,244	2,826	23.58	42.90	54	46
9	814	1,813	16.62	23.46	57	43
10	1,494	1,322	24.10	20.68	47	53
Bird 22						
1	16,346	10,932	141.22	86.00	55	70
2	3,399	3,291	26.30	33.14	49	51
3	2,456	2,393	56.52	64.78	58	42
4	10,339	9,080	92.46	78.98	43	57
5	10,985	5,975	151.78	74.56	41	36
6	14,998	10,611	124.82	102.40	29	26
7	5,256	18,771	48.62	177.52	26	25
8	2,132	4,247	17.58	46.08	40	60
9	1,436	2,546	9.96	25.88	49	51
10	1,990	1,732	16.06	19.18	49	51

## APPENDIX (Continued)

Condition	Responses		Minutes		Reinforcers	
	Left	Right	Left	Right	Left	Right
Bird 23						
1	7,453	3,662	135.14	91.44	71	51
2	2,619	1,180	41.36	21.18	57	43
3	4,252	2,062	63.34	62.52	55	45
4	5,707	2,247	91.14	83.34	48	52
5	6,720	3,128	114.64	112.74	40	35
6	6,269	2,510	113.60	114.14	21	32
7	4,425	4,659	58.30	170.24	30	23
8	1,425	2,431	19.38	50.06	56	44
9	949	1,882	11.58	30.80	45	55
10	1,215	1,413	15.22	22.24	46	54
Bird 24						
1	6,507	4,094	165.92	66.34	70	53
2	942	2,549	19.20	54.02	38	62
3	1,913	3,421	42.32	83.84	39	61
4	3,736	3,186	109.96	98.32	62	38
5	3,238	3,265	102.60	124.14	38	33
6	2,852	2,519	122.00	103.46	22	30
7	2,655	4,243	83.86	145.14	30	24
8	706	2,158	21.34	47.38	52	48
9	798	1,287	15.44	29.56	53	47
10	687	1,716	12.12	31.10	40	60
Bird 25						
1	8,891	8,343	137.90	91.38	58	67
2	3,577	3,951	33.70	34.34	56	44
3	6,711	6,939	49.64	62.28	43	57
4	6,279	6,986	104.76	71.14	55	45
5	10,384	8,269	135.66	91.60	41	36
6	15,064	8,527	148.10	81.48	32	24
7	12,035	21,078	90.76	139.98	31	23
8	3,879	4,725	34.36	30.26	55	45
9	2,143	2,533	15.90	19.86	50	50
10	2,687	1,638	20.00	14.38	50	50
Bird 26						
1	10,597	7,646	136.34	88.14	58	65
2	4,074	1,163	36.70	24.72	50	50
3	8,328	3,070	73.62	47.48	49	51
4	10,715	3,925	123.44	49.04	51	49
5	11,137	4,448	147.10	80.94	32	43
6	14,918	4,627	147.34	81.16	31	26
7	6,982	8,058	51.06	177.24	24	31
8	2,137	2,079	19.62	46.78	49	51
9	1,400	1,487	10.60	33.58	44	56
10	2,525	993	19.48	19.30	55	45