

*PERFORMANCE ON CONCURRENT VARIABLE-INTERVAL
EXTINCTION SCHEDULES*

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Six homing pigeons were trained on concurrent variable-interval extinction schedules in a switching-key procedure. The discriminative stimuli and associated schedules in operation were selected randomly after each switch and each reinforcer. More than 80 daily sessions were arranged in each of five experimental conditions that varied the reinforcer rate on the variable-interval schedule. Behavior allocation remained nonexclusive even after extended training and did not change systematically as a function of the reinforcer rate. Both of these findings are predicted by a contingency-discriminability description of choice and are incompatible with a generalized matching description.

Key words: behavior allocation, concurrent schedules, extinction, generalized matching, contingency discriminability, pecking, pigeons

The generalized matching law (Baum, 1974) accurately describes the relative allocation of behavior (responses and time) between alternatives in typical two-alternative concurrent variable-interval (VI) choice situations. The law may be written

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

where B measures responses or times spent responding, and R measures obtained numbers of reinforcers. The parameter c is called bias, and it measures any constant proportional preference for B_1 versus B_2 that is independent of the variation in R_1 and R_2 . The parameter a is called sensitivity to reinforcement, and it measures the proportional change in the log behavior ratio when the log reinforcer ratio is varied. Although this law has been highly successful in describing data from choice research (Davison & McCarthy, 1988), there are areas in which it does not predict particularly well, and recently the two parameters a and c have often been used more as higher order measures of performance than as theoretical entities. For instance, both White, Pipe, and McLean (1984)

and Miller, Saunders, and Bourland (1980), following a suggestion by Baum (1979), have used the parameter a to measure the discriminability between the stimuli that signal the alternatives in concurrent schedules.

Equation 1 makes some clear predictions. First, the relation between log response and log reinforcer ratios should be a straight line with slope a over all changes in log reinforcer-ratio values. A corollary to this is that when one alternative provides no reinforcers (an extinction schedule), responding should be exclusively to the alternative that provides the reinforcers. The first prediction was systematically investigated by Davison and Jones (1995) by varying log reinforcer ratios over a much wider range than had previously been used. They reported nonlinearities in the log response–reinforcer relation at high ratios, and they argued that their data were more consistent with a molar choice model proposed by Davison and Jenkins (1985):

$$\log\left(\frac{B_1}{B_2}\right) = \log\left(\frac{d_r R_1 + R_2}{d_r R_2 + R_1}\right) + \log c. \quad (2)$$

The variables, and the parameter c , are the same as in Equation 1. The term d_r is called contingency (or response–reinforcer) discriminability, and it measures the degree to which the subject discriminates each response–reinforcer relation. Its value varies from 1 (no discrimination, and $a = 0$) to infinity (perfect discrimination, and $a = 1$). This equation predicts that the relation between log response and reinforcer ratios is nonlinear, with diminishing preference changes with more

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extreme reinforcer ratios. The corollary to Equation 2 is that there is a limiting noninfinite value for the response ratio when $\log(R_1/R_2)$ is infinite. Assuming that R_2 is zero, Equation 2 becomes

$$\log\left(\frac{B_1}{B_2}\right) = \log d_r + \log c. \quad (3)$$

Unlike Equation 1, Equation 3 predicts that as long as d_r is not infinite, responding will be maintained on the extinction alternative. Further, Equation 3 predicts that the log response ratio in concurrent VI extinction schedules will be independent of the value of R_1 , the VI schedule value, which does not appear in Equation 3. Notice that the generalized matching law cannot predict nonexclusive responding in concurrent VI extinction schedules even if the value of a is supposed to measure stimulus discrimination between the alternatives, because the predicted $\log(B_1/B_2)$ for concurrent VI extinction remains infinite as a is decreased from 1 to 0. The generalized matching law also predicts no effects of VI reinforcer rate on response allocation in concurrent VI extinction, but only in the sense that that the response ratio will always be infinite.

There is evidence for the prediction that responding is maintained on both alternatives on concurrent VI extinction schedules. Davison and Hunter (1976) arranged a series of two- and three-alternative concurrent VI schedules, with a number of cases in which one alternative was extinction. The schedules were arranged on different keys, so presumably d_r was high. Despite this, without fail, some responding was maintained to the extinction alternative. The same result, from a single condition, was reported by Davison and Jones (1995). Baum (personal communication, February 1995) argued that the number of sessions arranged in these experiments was insufficient, and that responding would be eliminated on the extinction alternative after extended exposure. Indeed, increasing preference with increasing exposure has been documented in concurrent VI VI (Todorov, Castro, Hanna, Bittencourt de Sa, & Barreto, 1983).

Although Davison and Hunter's (1976) data could be used to test the prediction that response ratios in concurrent VI extinction

performance are independent of the reinforcer rate on the VI schedule, their data were not sufficiently extensive to make a satisfactory test. The present experiment was designed to look at performance on concurrent VI extinction schedules when the VI reinforcer rate was extensively varied over conditions in order to test the above predictions of Equation 2. To alleviate concerns about the amount of training, each condition was conducted for more than 80 sessions. Also, to insure that subjects could not discriminate the response-reinforcer alternatives by using win-stay/lose-shift strategies, the random switching procedure introduced by Alsop and Davison (1991) was used. In this, the alternative arranged on the main key and its associated stimulus were randomly changed after each switching response and each reinforcer (i.e., the same signal was presented with $p = .5$). The procedure avoids the possibility that response allocation could be affected by the absolute difference in reinforcer rates between the alternatives, with it being easier to discriminate concurrent VI 10 s extinction from concurrent VI 360 s extinction. Finally, the response-reinforcer discriminability (d_r in Equations 2 and 3) was maintained at less than infinity by signaling the two alternatives with two moderately discriminable intensities of light (as in Davison & Jones, 1995). Under these conditions, if we find that response ratios are noninfinite and are constant with respect to changes in the VI reinforcer rate, we will have produced further evidence that supports Equation 2, rather than Equation 1, as a description of performance on concurrent VI VI and concurrent VI extinction schedules.

METHOD

Subjects

The same 6 homing pigeons as used by Davison and Jones (1995), numbered 21 to 26, were maintained at $85\% \pm 15$ g of their free-feeding body weights. Water and grit were always available in their home cages, and they were fed an appropriate amount of mixed grain immediately after the daily training sessions to maintain their designated body weights.

Apparatus

The apparatus was the same as that used by Davison and Jones (1995). The subjects

Table 1

Sequence of experimental conditions, the schedule arranged on the bright and dim alternatives, and the number of sessions in each condition.

Condition	Schedule		Sessions
	Bright	Dim	
1	Ext	VI 15 s	85
2	VI 240 s	Ext	105
3	Ext	VI 10 s	80
4	VI 360 s	Ext	120
5	Ext	VI 60 s	95

worked in a standard sound-attenuating experimental chamber that was 330 mm high, 300 mm wide, and 330 mm deep. Two pecking keys, 20 mm in diameter, were situated on one wall of the chamber, 130 mm apart and 260 mm above the grid floor. The keys required about 0.1 N for operation. Centered on the same wall, 100 mm from the floor, was a food magazine that contained wheat. During reinforcement, the keys were darkened and the food magazine was raised and lit for 3 s. There was no chamber illumination other than the lit keys and the magazine light.

All experimental contingencies were controlled by a remote PC-compatible computer running MED-PC® software, and all data were collected within the program.

Procedure

Because the pigeons had extensive previous experience in the experimental situation, no magazine or key-peck training was required, and they were placed immediately on the first condition of the experiment (Table 1).

The procedure was the same as used by Davison and Jones (1995). During the session, the left key was transilluminated with one of two intensities of yellow light (0.9 or 0.75 cd/m²), and the right key was transilluminated by red light. In the switching-key procedure used, pecks on the left (main) key were reinforced on various pairs of VI extinction or extinction VI schedules that were changed over conditions (Table 1), and pecks to the right (switching) key could change (with a probability of .5) the intensity of the left keylight and the associated schedule. After a switching-key peck, there was a change-over delay (Herrnstein, 1961) of 3 s, during which time no reinforcers could be obtained

for pecking the left key. Effective changeovers could be emitted during the changeover delay. Following the delivery of a reinforcer, the schedule and associated stimulus arranged on the left key were selected with a probability of .5.

Sessions commenced in blackout, lasted until 40 reinforcers had been obtained or until 45 min had elapsed, whichever occurred first, and ended in blackout.

A condition remained in effect for all 6 subjects until plots of log response and time ratios averaged over five-session blocks looked stable to the experimenters, who tried to use very strict, though informal, criteria. This took between 80 and 105 sessions (Table 1).

The data collected were the times of each response and reinforcer event in each experimental session. Overall time-allocation data were calculated by cumulating the times from each switching response to the next. Averages over five-session blocks, commencing at the 21st to 25th session, were used in the data analysis for all conditions.

RESULTS

Figures 1 and 2 show log response- and time-allocation ratios, respectively, during training in each experimental condition for all birds, plotted in five-session blocks. (Response rates from the last block are shown in the Appendix.) Some results are immediately evident: First, neither measure of choice became consistently exclusive over continued blocks of training (although there were a few individual sessions with exclusive responding). For most subjects in most blocks, absolute log preference ratios were between 1 and 2 (10:1 and 100:1). Second, the block-to-block variation in log behavior (time and response) ratios was surprisingly large. However, with response ratios of this size, just a small variation in sessional responses to the extinction alternative will produce large changes in behavior ratios. Third, a comparison of Figures 1 and 2 shows that there was no consistent difference between response- and time-allocation measures under concurrent VI extinction. Fourth, we are totally unable to explain the performance of Bird 24 in Condition 2. There was a small but consistent difference between response allocation in this condition (Figure 1) and the appro-

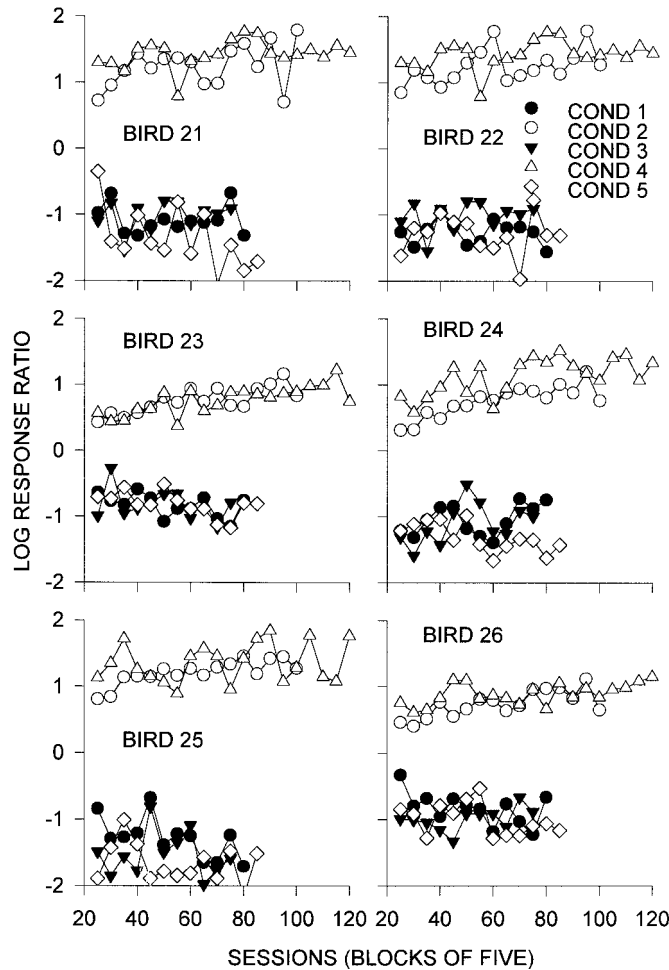


Fig. 1. Log response-allocation ratios as a function of training sessions (averaged over blocks of five sessions) for all subjects.

appropriate comparison, Condition 4. However, on time-allocation measures (Figure 2), performance on Condition 2 can be seen as extremely deviant, with large amounts of time spent switched into the extinction alternative. However, the increasing trend (Figure 2) suggests that this errant performance might have been eliminated by extended training.

Also evident from Figures 1 and 2 is that behavior allocation did get progressively more extreme with training, but in general this change occurred at a low rate. It is difficult to assess this trend adequately, and indeed to demonstrate that it had ceased by the time conditions were terminated. Looking at the trends using a linear regression between log behavior ratio and session number

showed that significant increases (slopes more than two standard errors away from zero) occurred for all subjects, except Bird 21 in Condition 2 (VI 240 s) and Birds 22, 23, 24, and 26 in Condition 4 (VI 360 s). There were no significant trends in the other conditions, except for Bird 25 in Condition 1 (VI 15 s). Whether it is a matter of chance that most of the significant trends occurred in the two lowest reinforcer-rate conditions is moot, although an argument might be mounted that small differentials in reinforcer rates between the alternatives might lead to slower behavior change. However, Mazur (1992) found no difference in the rate of change of response ratios after transitions to three different concurrent VI VI reinforcer ratios.

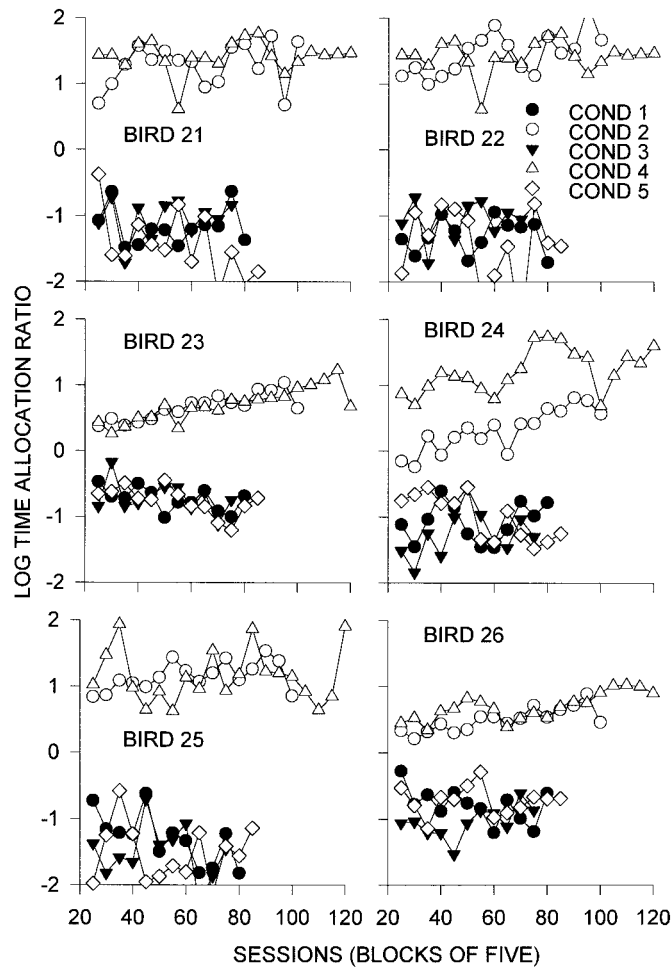


Fig. 2. Log time-allocation ratios as a function of training sessions (averaged over blocks of five sessions) for all subjects.

Most often, in stable-state choice research, data are collected after 15 to 30 sessions of training. It is of interest, therefore, to compare five-session block performance at 25 sessions with performance in the last five sessions of all conditions of the present experiment. This analysis showed that there were significant differences between performance after these differing amounts of training (sign test, $z = 3.10$ for both response and time allocation). These analyses thus confirm the significant trends in the above analysis.

Figure 3 shows log response and time ratios for the final five sessions of each condition as a function of the arranged number of reinforcers per minute on a common-log scale. The approximate constancy of the preference

measures across reinforcer rates was confirmed by nonparametric trend tests (Ferguson, 1971), which showed that there was no significant change in either response or time measures for the group. It can also be seen that, as in the comparison of Figures 1 and 2, response and time measures were similar. Thirteen of 30 comparisons showed time allocation to be more extreme than response allocation, which is not significant on a binomial test at $p = .05$.

DISCUSSION

The present experiment showed that behavior allocation on concurrent VI extinction schedules was not exclusive to the VI alter-

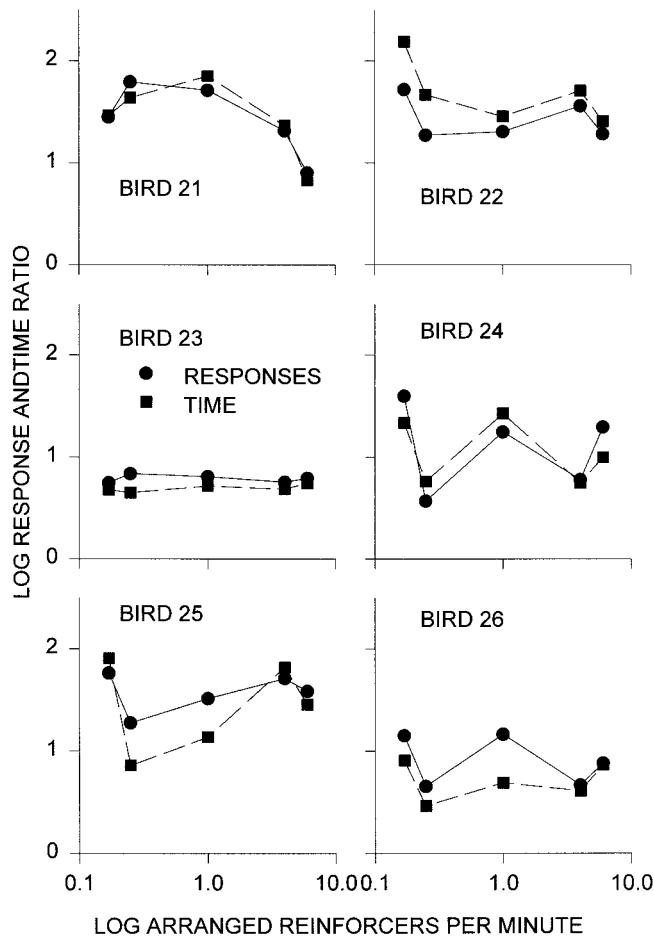


Fig. 3. Log response and time allocation measured over the last five sessions of each experimental condition as a function of the log of the arranged number of reinforcers per minute on the VI schedule.

native when the stimuli that signaled the alternatives were moderately discriminable (Figures 1 and 2). This was true even after extended training in 80 or more experimental sessions. Although, in some conditions, for some subjects, it could be argued that behavior allocation was still increasing after 80 to 120 sessions, this was not the case for other subjects and conditions. This result is not easily described by the generalized matching relation (Equation 1), which must predict that behavior allocation on concurrent VI extinction is infinite even if sensitivity to reinforcement (a) is very low.

Second, Figure 3 and the associated analyses showed that, after extended training, there were no significant trends in behavior allocation across the various arranged VI re-

inforcer rates. This result is predicted by the Davison and Jenkins (1985) model of concurrent-schedule performance. In summary, then, the present research argues both against the generalized matching law as an effective general model of choice and for its replacement by the contingency-discriminability model (Equation 2).

However, the finding that behavior ratios continued to become more extreme from Sessions 21 to 25 to the end of training on a condition is problematic. It seems that this slow stabilization effect is not limited to concurrent VI extinction schedules, in that Todorov et al. (1983) reported what appears to be a similar change in preference with training on concurrent VI VI schedules (see their Figures 3 and 4). For 3 of their 4 birds, and

for both response and time measures, sensitivity-to-reinforcement values (a in Equation 1) were greater at 55 sessions than they were at 25 sessions. Although that result does not approach statistical significance, the trend is in the same direction as found here. Todorov et al. suggested that increasing the number of sessions per condition increased the chance of gaining a sensitivity (a , Equation 1) value close to 1.0. The present research shows that choice increases but that sensitivity to reinforcement is not an effective measure of the increasing behavior ratio. In terms of the contingency-discriminability model, d_r increases with increased training, and the reason for this is unknown. This slow increase in behavior ratios, and the finding by Todorov et al. that sensitivity decreases with increasing exposure to different reinforcer ratios, are consistent with additive models of behavior allocation (e.g., the cumulative-effects model, Davis, Staddon, Machado, & Palmer, 1993).

What, then, is the scientific status of the large amount of data collected after 15 to 30 sessions on concurrent VI VI schedules, and what does the slow increase in sensitivity mean for concurrent-schedule research? Most researchers use either explicit or implicit stability criteria in their research (Killeen, 1978). The problem for such criteria, highlighted by the present data, is that when one finds very slow trends, with quite large block-to-block variances, stability criteria have to be exceedingly sensitive to work effectively. Indeed, if we are interested for theoretical reasons in final asymptotic performance, there may never be a point at which we can be satisfied that the trend had ceased. Two assumptions can be made about the present data: (a) The monotonic trend that we found between the 25th session and the final sessions of each condition would continue linearly without end. This seems rather unreasonable, and indeed such a trend will not account for performances before the 25th session (see Todorov et al., 1983). (b) We might assume that the trend is nonlinear and has an asymptote. Killeen (1978, Experiment 1) used a simple exponential function in his investigation of stability criteria:

$$R = A(1 - e^{j/c}), \quad (4)$$

where R is the dependent variable value, A is the asymptote, j is the session number, and c

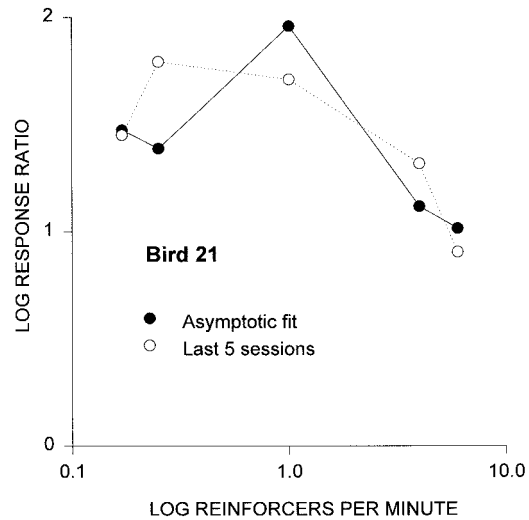


Fig. 4. Log response ratios averaged over the last five sessions of each condition, and the asymptotic log response ratios predicted by fitting Equation 4, as a function of the log of the arranged reinforcers per minute on the VI schedule.

is a curvature constant. Rather than being interested in stability criteria per se, here we are more interested in whether approaching the data in this way will produce a reasonable and accurate estimate of the asymptote. If this can be done, then running conditions to stability may be less important than collecting sufficient *transitional* data so that the asymptotic performance can be accurately estimated. Indeed, theoretical stable-state parameters, be they a in Equation 1 or d_r in Equation 2, can, and have been, predicted from nonstable performances (e.g., Hunter & Davison, 1985; see also Belke & Heyman, 1994). To illustrate this approach, Equation 4 was fitted to the data from Bird 21 (selected at random), and both the mean log behavior ratio from the final five sessions and the predicted asymptotes from the fits are shown in Figure 4. The data were not systematically different from the predicted asymptotes, suggesting that performance had generally stabilized by the end of training in each condition.

Note, however, that a stability criterion based on the exponential equation, as discussed by Killeen (1978), will not necessarily provide accurate asymptotic data. Killeen's stopping criterion was that the behavior-change process was at least 99% of the way to completion, and the average of the last six

sessions had to be within 5% of the predicted asymptote. In general, data (e.g., the average of the last six sessions) from using such a criterion will systematically underestimate the true asymptote, especially if the approach to the asymptote is smooth with no overshooting. Under these conditions, the *predicted* asymptote would provide generally more accurate estimates of stable-state performance than the data obtained when a stability criterion has been satisfied. Some might object to using an estimate, rather than a straight-forward calculation based on obtained data, to determine stability. We believe, however, that this approach to behavior analysis should be at least considered.

In conclusion, the present research has questioned the ability of the generalized matching law (Equation 1) to describe performance in concurrent VI extinction schedules. It will be argued that our use of less than perfectly discriminable discriminative stimuli to signal the alternatives will force less than exclusive responding to the VI alternative. This, of course, is true. But two points have to be made: (a) This procedure does not force a constant preference ratio that is independent of the VI reinforcer rate, and (b) the generalized matching law currently has no mechanism to predict any result other than exclusive preference on concurrent VI extinction schedules. We argue that the contingency-discriminability model does a good job of describing concurrent VI schedule results in their entirety. An alternative argument would be that the generalized matching law does not provide an adequate description of the effects of stimulus disparity in concurrent schedules, and that it needs to be extended to do so. Note that this latter argument accepts that the value of sensitivity to reinforcement is not an appropriate measure of stimulus control in concurrent schedules. How such an extension might be achieved is unclear but deserves research, because it is clear that a general understanding of choice *requires* an understanding of how choice is discriminatively controlled.

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APPENDIX

The number of responses per minute emitted in the last five sessions of each condition on both concurrent-schedule alternatives for all subjects.

Condi- tion	Subject											
	21		22		23		24		25		26	
	Bright	Dim	Bright	Dim	Bright	Dim	Bright	Dim	Bright	Dim	Bright	Dim
1	4.51	93.50	2.03	73.88	29.36	166.71	12.58	70.26	3.23	166.01	21.93	101.90
2	82.01	1.32	26.24	1.40	88.41	12.85	24.23	4.21	60.55	3.21	64.54	14.34
3	13.38	107.54	4.11	79.67	32.54	201.76	7.41	73.77	5.19	200.01	15.81	120.62
4	84.98	3.01	7.60	0.15	41.18	7.35	29.20	1.35	83.46	1.44	93.57	6.62
5	1.76	90.76	2.08	42.29	15.77	101.19	1.66	44.60	2.83	92.78	6.64	97.27