INTERVAL REINFORCEMENT OF CHOICE BEHAVIOR IN DISCRETE TRIALS¹

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Pigeons were trained to peck at red or green keys presented simultaneously in discrete trials. In one experiment, reinforcements were arranged by concurrent variable-interval schedules. The proportion of responses to green approximately matched the proportion of reinforcements produced by pecking green. Detailed analysis of responding revealed a systematic decrease in the probability of switching from green to red within sequences of trials after reinforcement. This trend corresponded to sequential changes in the relative frequency of reinforcement, and not to sequential changes in probability of reinforcement. In a second experiment, reinforcements were scheduled probabilistically every seventh trial. Even though there were no contingencies on pecking during the first six post-reinforcement trials, choices of green on the first response after reinforcement matched the proportion of reinforcements for pecking green. These results extend the generality of overall matching under concurrent reinforcement.

The effects of reinforcement schedules have usually been studied by analyzing the average rate of emission of a single response, the pattern of responding in time after reinforcement, and the distribution of interresponse times. These measures are to some extent independent: the same average rate may result from quite different temporal patterns or interresponse-time distributions. However, these three aspects of behavior may be controlled by the same independent variables: frequency or relative frequency of reinforcement affects average response rates (e.g., Catania and Reynolds, 1968), the rate of responding at various times after reinforcement (Catania and Reynolds, 1968), and the probability of responding in time after a preceding response (Anger, 1956; Shimp, 1968; Staddon, 1968). The present paper attempts a similar analysis of the variables controlling choices between two simultaneously available responses.

Skinner (1950) first brought the analytic methods of free-operant research to bear on choice behavior by studying two continuously available responses maintained by independent schedules of reinforcement. More re-

cently, asymptotic performances maintained by concurrent variable-interval (VI) schedules have been studied parametrically, and strikingly lawful data have been obtained. Within various procedural arrangements, Herrnstein (1961), Catania (1963), Reynolds (1963), and Pliskoff, Shull, and Gollub (1968) demonstrated that the overall relative frequency of one response matches the relative frequency of reinforcement produced by that response. There is relatively little information on detailed patterns of responding in these free-operant choice studies. Reynolds (1963) examined switches between keys as a function of obtained relative frequency of reinforcement, and found departures from a simple matching relation at this level of analysis. The boundary conditions for the overall matching relation have not been explored in detail, but it is known that independence of the two responses and schedules is important (Catania, 1966).

Traditionally, choice behavior has been studied in discrete-trial settings that provide well-defined response opportunities and permit direct estimation of response probabilities (Bush, Galanter, and Luce, 1963). This sort of design has been especially common in studies of discrimination learning in which responses to one stimulus are regularly reinforced and responses to another, simultaneously presented stimulus are never reinforced. Because the standard simultaneous discrimination procedure may be seen as a

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limiting case of concurrent schedules with non-zero reinforcement frequencies for responding to both stimuli, similar methods may be valuable in the more general case.

Shimp (1966) studied discrete-trial choices with probabilistic reinforcement that mimicked certain contingencies of concurrent VI schedules and observed matching between the relative frequencies of choices and reinforcements. His analysis suggested that the subjects tended to respond to that alternative with the momentarily higher probability of reinforcement, which he termed momentary maximizing. He argued that matching resulted from this maximizing tendency. Herrnstein (in preparation) has also examined choices in discrete trials with concurrent VI reinforcement and observed overall matching. The present experiments provided further data on this situation. Specifically, choices were permitted on discrete trials. Reinforcements were scheduled concurrently at variable intervals (in effect, after variable numbers of trials), or after a fixed number of trials. Asymptotic performances were examined for dependencies on prior reinforcements and choice sequences in an attempt to understand the determinants of responding.

EXPERIMENT I

METHOD

Subjects

Three experimentally naive male White Carneaux pigeons were maintained at 80% of their free-feeding weights.

Apparatus

The experiment was conducted in a Lehigh Valley three-key pigeon chamber with red and green keylights, houselight, grain magazine, and white noise source. The center key was always dark. The experiment was scheduled by standard relay equipment in a separate room. Data were recorded on counters and an event recorder.

Procedure

The subjects were trained to peck the side keys, and given equal numbers of regular reinforcements for pecking red or green on the right or left. They were then exposed to the following procedure. A trial began with illu-

mination of both keys, one red and one green. A peck on either key turned off both keylights for an intertrial interval of 6 sec. If no peck occurred within 2 sec, the keys were darkened for 6 sec. Pecks on dark keys extended the intertrial interval for 6 sec from the peck. The subjects rarely pecked dark keys more than four or five times per session. Responses on the green key were reinforced with 4-sec access to grain if a VI 1-min tape had scheduled reinforcement during the preceding intertrial interval, and responses on the red key were reinforced if an independent VI 3-min tape had made reinforcement available. The VI 1-min tape consisted of 11 arithmetically spaced intervals ranging from 10 to 110 sec, and the VI 3-min tape consisted of nine arithmetically spaced intervals ranging from 10 to 350 sec. The positions of the tapes were changed irregularly each day to prevent them from getting into phase with each other or with the beginning of a session. Once a reinforcement was scheduled for a particular color, it remained available until produced by a response to that color. Both tapes ran continuously during trials and intertrial intervals unless a reinforcement had become available, in which case the tape that set up reinforcement stopped until that reinforcement was produced.

For the first 23 sessions, red and green alternated irregularly on the right and left keys. Since reinforcements remained available until produced, it was possible for the birds to obtain all scheduled reinforcements by responding exclusively to one key, and all three subjects developed strong position preferences. To overcome this, the key colors changed sides every 3 min. If the keys were lighted at the expiration of a 3-min period, the change was postponed until the keys were dark. This procedure resulted in a substantial loss of reinforcements unless the birds pecked each key at least occasionally in each 3-min period. The latter arrangement was in effect for an additional 50 to 60 sessions. After this training, food reinforcement was omitted for 10 sessions, and then reinstated for 15 sessions. Throughout the study, sessions lasted 30 min and were scheduled daily unless a bird exceeded its 80% weight by 15 g.

RESULTS

Probability of responding given a trial, and probability of responding to green given that

the subject responded, were computed for each session and averaged across subjects. The results for the final seven sessions of training, 10 sessions of extinction, and 15 sessions of reconditioning are presented in Fig. 1. The plot indicates that the birds virtually always responded given a trial, and that about 75% of their responses were to the green key, matching the scheduled relative frequency of reinforce-

ment. Probability of responding declined in an orderly curve during extinction, accompanied by a gradual reduction in choices of green until a level near 0.50 was reached. The original performance was rapidly reestablished when reinforcement was reinstated. The average was representative of all three birds, as indicated by the summary statistics shown in Table 1.

Fig. 1. Probability of responding given a trial, and probability of pecking green given that a response occurred, during the final seven of approximately 60 training sessions, 10 sessions of extinction, and 15 sessions of reconditioning. The data are averages for three pigeons. The light dashed line at 0.75 indicates the scheduled relative frequency of reinforcement.

Table 1
Summary Data for Selected Portions of Exp. I

	Bird No.	Responses			Reinforcements		
		G	R	$\frac{G}{G+R}$	G	R	$\frac{G}{G+R}$
Three sessions preceding extinction	58	542	133	0.80	84	24	0.78
	59	468	192	0.71	81	27	0.75
	60	490	222	0.69	83	28	0.75
Final three sessions of extinction	58	66	45	0.59	—	—	—
	59	16	23	0.41	—	—	—
	60	30	26	0.54	—	—	—
Final eight sessions of reconditioning	58	1434	311	0.82	222	60	0.79
	59	1235	448	0.73	214	70	0.75
	60	1297	464	0.74	212	69	0.75

Data for the final eight sessions of the experiment were analyzed in detail. As shown in Table 1, Birds 59 and 60 obtained exactly 75% of their total reinforcements for pecking green, and the proportion of responses to green matched this value almost perfectly. Bird 58 made 82% of its responses to green, and produced 79% of its reinforcements by pecking green, so that its relative frequency of responses to green departed only slightly from the obtained relative frequency of reinforcement.

All three birds exhibited position preferences. To show this, the relative frequency of responses to green was determined for five-trial blocks immediately before and after each change from green on the left to green on the right, and *vice versa*. The results are presented in Fig. 2. Although it is clear that key position affected the tendency to peck green, it is equally clear that the birds were not simply perseverating on the key most recently associated with the VI 1-min schedule. Instead, their probabilities of choosing green changed abruptly by about ± 0.10 when the key colors changed sides.

Choices on trials immediately after reinforcement were broken down according to whether reinforcement had been produced by pecking red or green. Because of the 10-sec minimum interval on both tapes, at least two trials should elapse between reinforcements for successive pecks at a single color. In practice, intertrial pecks occasionally lengthened the intertrial interval so that two reinforcements could be produced by pecking the same color on two successive trials, but an analysis of the data showed that this was rare. The probabilities of reinforcement for pecking red or green on the first trial after reinforcement, subdivided according to reinforcement on the previous trial, were estimated by dividing the numbers of reinforcements produced by the numbers of responses recorded on these trials. As shown in Table 2, reinforcement was more probable for pecking red after reinforcement for pecking red than for pecking red, and *vice versa*. If the subjects conformed to this aspect of the schedule contingencies, the probability of pecking red after reinforcement on green should be high, and the probability of pecking red after reinforcement on red should be low. This was not the case. As shown in Table 2, only one subject exhibited an appreci-

able effect in that direction, and there was no difference in the pooled data.

Arithmetic variable-interval schedules make reinforcement increasingly probable as a function of time since reinforcement (Catania and

Fig. 2. Proportions of responses to green during the last five trials of a block with green on the left, the first five with green on the right, the last five with green on the right, and the first five with green on the left. Data were pooled for the final eight sessions of reconditioning.

Table 2

Obtained probabilities of reinforcement for pecking red or green on the first trial after reinforcement for pecking red or green, and the probability of pecking red rather than green on these trials. Data are given for individual subjects, and pooled across subjects for the final eight sessions of Exp. I.

	Probability of reinforcement				Probability of pecking red	
	Green after green	Green after red	Red after green	Red after red	After green reinforcement	After red reinforcement
#58	0.01	0.33	0.42	0.00	0.24	0.17
#59	0.03	0.20	0.18	0.08	0.34	0.41
#60	0.00	0.24	0.14	0.05	0.36	0.34
Pooled	0.01	0.26	0.33	0.05	0.31	0.32

Reynolds, 1968). Because of the differences in the mean and maximum interreinforcement intervals in the present schedules, the probability of reinforcement for pecking green increased more rapidly than that for pecking red. With the passage of successive trials after reinforcement, therefore, it became increasingly likely that the next reinforcement would be produced by pecking green rather than red. To check on the actual operation of the present VI schedules, the numbers of reinforcements produced by pecking red or green at each ordinal trial after reinforcement were determined for each subject. These numbers were pooled to calculate the proportion of reinforcements produced by pecking red at each trial number. This function is displayed in the upper panel of Fig. 3. The proportion of reinforcements produced by pecking red decreased from about 0.50 to about 0.15 over the course of nine trials. Too few long runs were available to permit reliable estimation beyond this point.

A similar analysis was performed to assess trends in the probability of pecking red rather than green at each ordinal trial number. Individual data are presented in the lower panel of Fig. 3. Beyond the initial decrease in the tendency to choose red after reinforcement, there is little evidence of a consistent trend in the data. These data were pooled without regard for the color of the key pecked to produce the previous reinforcement because the prior reinforcement evidently had no systematic effects on post-reinforcement choices (Table 2).

An alternative analysis leads to examination of prior responses rather than reinforcements. Because concurrent VI schedules run continuously until reinforcement is available, the

probability of reinforcement for one response is an increasing function of time spent emitting the other response. In the present situation, for example, the probability of reinforcement for switching from green to red should be an increasing function of the number of consecutive trials on which the green key was pecked. The data were examined to determine whether this aspect of the schedules in fact had

Fig. 3. Upper panel: the proportion of reinforcements obtained for pecking red as a function of the ordinal number of a trial after reinforcement. The function was determined from the number of reinforcements produced by pecking red or green at each ordinal trial, pooling across subjects, and dividing reinforcements for pecking red by total reinforcements for each trial. Lower panel: the probability of pecking red as a function of the ordinal number of a trial after reinforcement. Data for individual subjects are taken from the final eight sessions of Exp. 1.

an effect. The analysis was performed only for switches from green to red, because every subject recorded at least 25 runs of 10 or more consecutive pecks on green during the sessions under consideration, whereas they rarely pecked the red key on more than three or four successive trials. The numbers of responses producing reinforcement were determined separately for switching to red and for continuing on green as a function of the number of consecutive responses to green. The data were pooled across subjects and the probabilities of reinforcement calculated. The results are displayed in the upper panel of Fig. 4. The figure shows that the probability of reinforcement for switching to red increased with successive choices of green, as expected from the properties of VI schedules, while the probability of reinforcement for pecking green remained substantially constant. The latter statement apparently contradicts the statement that the probability of reinforcement for pecking red relative to that for pecking green decreased with successive trials (Fig. 3). The difference between these aspects of the schedule contingencies may be understood by appreciating that the analysis presented in Fig. 3 was based on trial sequences that began anew with each reinforcement, regardless of the key color pecked at any point in a sequence, whereas the analysis in Fig. 4 was based on trial sequences that began anew with each red-key response, without regard for whether it was reinforced or whether there were intervening reinforcements for pecking green.

The probability of switching from green to red, as a function of successive green pecks, is shown in the lower panel of Fig. 4 for individual subjects. In each case, the probability of switching from green to red decreased with successive choices of green. In this respect, then, none of the subjects conformed to the schedule contingencies.

As noted above, the data presented in Fig. 3 were pooled without regard for response sequences in an attempt to isolate the effects of prior reinforcement, and the data represented in Fig. 4 were pooled without regard for reinforcements in an attempt to evaluate the effects of prior choices. Both analyses are complicated by possible interactions between response sequences and reinforcements. A final analysis examined both determinants of responding. The probability of pecking red was

evaluated as a function of the number of consecutive responses to green after reinforcement, so that all responses after the first red-key peck in each post-reinforcement sequence of trials were excluded. This substantially reduced sample size because there were few long runs of green-key pecks not interrupted by reinforcement. However, sufficient data were available to estimate trends over seven to nine trials for individual subjects. The resulting functions are presented in Fig. 5, which is simi-

Fig. 4. Upper panel: the probability of reinforcement for pecking green, and for switching to red, as functions of the number of successive choices of green. The functions were obtained by pooling across subjects the numbers of reinforcements obtained for continuing on green or switching to red, and dividing by pooled numbers of responses to green or red at each number of previous successive choices. Lower panel: Probability of switching from green to red as a function of the number of successive responses to green. The functions were based on the final eight sessions of Exp. 1. Probability of switching was calculated on the basis of the number of opportunities for switching at each run length. All three birds had at least 25 opportunities to emit runs of 10 or more responses.

lar to Fig. 4 in showing systematic decreases in the probability of switching to red as a function of the number of green pecks.

This decreasing trend agrees with the inverse relation between the proportion (or relative frequency) of reinforcements for pecking red and the number of trials since the previous reinforcement (Fig. 3). It does not accord with changes in the probability of reinforcement as estimated from reinforcements per response. To show the separation between these aspects of the reinforcement contingencies within the present restricted set of data, the numbers of reinforcements obtained for pecking red or green after different numbers of consecutive green pecks after reinforcement were determined and pooled into three-trial blocks because of the small sample size. The probability of reinforcement for pecking red or green was determined by dividing the number of reinforcements by the number of responses emitted in each block. The relative probability of reinforcement was determined by dividing the probability of reinforcement for pecking red by the sum of the reinforcement probabilities in each block. Finally, the relative frequency of reinforcement for pecking red was determined by dividing reinforcements produced by red-key pecks by total reinforcements in each block. The results of these calculations are presented in Fig. 6. As in the larger sample considered in Fig. 3, the relative frequency of reinforcement for pecking red decreased with successive trials after reinforcement. As must be the case with arithmetic variable-interval

Fig. 5. Probability of pecking red as a function of successive choices of green after reinforcement. All responses after the first post-reinforcement response to red were excluded from the analysis. Probabilities were calculated on the basis of the number of opportunities for responding. No data points were plotted if there were fewer than 15 opportunities. Data for individual subjects were taken from the final eight sessions of Exp. 1.

schedules, the probabilities of reinforcement for pecking either red or green increased with successive trials after reinforcement, with the probability of reinforcement for pecking red remaining higher than that for green throughout the sequence of trials. These reinforcement probabilities covaried so that the relative probability of reinforcement remained constant over this range of trial sequences. This analysis suggests that choices were determined by the experienced relative frequency of reinforcement rather than by the probability of reinforcement.

EXPERIMENT 2

In Exp. 1, choices depended on maintained reinforcement, in that the probability of pecking green rather than red decreased to about 0.50 during extinction. That is, in the absence of any reinforcement contingencies, there was no systematic preference for green, despite its prolonged history of correlation with relatively

Successive Choices of Green After Reinforcement

Fig. 6. Probability of reinforcement for pecking green or red during blocks of three successive choices of green after reinforcement. The functions were obtained by dividing the pooled numbers of reinforcements for pecking green or red in each block of trials by the pooled numbers of responses to green or red, given that no previous response to red had occurred since reinforcement. Also shown on the same probability ordinate are the relative probability of reinforcement for pecking red (estimated by dividing the probability of reinforcement for pecking red by the sum of the reinforcement probabilities) and the relative frequency of reinforcement for pecking red (the number of reinforcements obtained by pecking red divided by total reinforcements obtained in each block of trials).

frequent reinforcement. As the foregoing analysis has shown, the contingencies of maintained reinforcement in that experiment were exceedingly complex and amenable to various analyses. The role of the contingencies may be separated from the maintenance of reinforcement by scheduling reinforcement at fixed intervals, without regard for responding during the interval. A procedure of this kind was employed in Exp. 2.

METHOD

Subjects and Apparatus

The subjects and apparatus were the same as in Exp. 1.

Procedure

The birds were exposed to the following reinforcement schedule for 37 sessions, beginning three weeks after completion of Exp. 1. Trials were scheduled as before, except that the left key was red and the right key green on every trial. On every seventh trial, reinforcement was made available for responses to either red or green by a probability randomizer set to assign 25% of all reinforcements to red, and 75% to green. Once a reinforcement was assigned to a color, it remained available until produced and no other assignments were made. This procedure guaranteed that obtained relative frequency of reinforcement approximately equaled the scheduled probability of reinforcement, and insured responding on both keys. No reinforcements were ever produced during the six trials immediately after reinforcement, and pecks during those trials in no way influenced the schedule.

Sessions lasted until 51 reinforcements were produced. No data were recorded until after the first reinforcement of each session. As before, sessions were run daily if the birds were within 15 g of their 80% weights.

RESULTS

The data for the last 10 sessions were analyzed to evaluate the probability of responding, and the probability of pecking the green key given a response, for each ordinal trial number after reinforcement. (Data for Bird 58 were lost for one session because of recording equipment failure.) These measures are given for all subjects in Fig. 7. In all cases, there was a systematic increase in the probability of re-

sponding as a function of trials after reinforcement. The probability of choosing green on the first trial after reinforcement, when responding was relatively infrequent, was substantially the same as on the seventh and subsequent trials when reinforcement was available and the birds nearly always responded. All subjects exhibited a slight elevation in choices of green at about the fourth or fifth trial after reinforcement, but otherwise there was no systematic effects.

Fig. 7. Probability of responding given a trial, and probability of pecking green given a response, as a function of the ordinal trial number after reinforcement. Reinforcement was scheduled only on the seventh trial, and held until collected. The functions are based on pooled data for the final 10 of 37 training sessions. The light dashed line at 0.75 indicates the scheduled relative frequency of reinforcement.

Further analysis determined how the birds chose on their first response after reinforcement, regardless of the trial number on which it occurred, and whether this choice depended on the response previously reinforced. The results are summarized in Table 3, which indicates that the overall probability of pecking green on the first response after reinforcement approximately matched the proportion of reinforcements for pecking green. Except for Bird 60, the immediately preceding reinforcement had only a small effect. These initial responses had no scheduled consequences, except for the extremely rare instances in which the birds paused for six or more trials after reinforcement. Also, responses on early post-reinforcement trials in no way influenced the probabilities of reinforcement on subsequent trials. Therefore, matching evidently occurred in the absence of any explicit contingencies between responding and reinforcement.

DISCUSSION

These experiments replicate the common finding of approximate overall matching between the relative frequencies of responses and reinforcements during maintained concurrent reinforcement. In Exp. 1, overall matching occurred in a situation involving complex contingencies between sequences of choices and reinforcement, which in part controlled changes in response probabilities during sequences of trials. In Exp. 2, approximate matching occurred on initial post-reinforcement choices despite the absence of any scheduled contingencies between those responses

and reinforcement. Therefore, these findings extend the generality of the matching relation for concurrent reinforcement.

Examination of the detailed structure of responding in Exp. 1 revealed a complex picture of the control of choice behavior by reinforcement. It may be well to begin by considering some aspects of performance which evidently were not controlled by the schedule contingencies. Post-reinforcement choices were not affected by the color of the key pecked to produce reinforcement on the previous trial, even though the obtained probabilities of reinforcement depended on the previous reinforcement (Table 2). Also, the probability of switching from green to red did not accord with changes in reinforcement probability with consecutive pecks at green (Fig. 4).

These findings differ from those reported by Shimp (1966). In his Exp. III, reinforcement was scheduled probabilistically for choices in discrete trials. The contingencies in his study were similar to those of VI schedules in that reinforcement remained available until produced. He observed that both the initial post-reinforcement choices and the changes in choice probabilities during sequences of trials between reinforcements corresponded approximately to differences in reinforcement probabilities arranged by the schedule. For these reasons, Shimp argued that overall matching was a byproduct of a tendency to choose that alternative with the higher probability of reinforcement on each trial.

The apparent failure of control by similar aspects of the reinforcement schedules in Exp. 1 is not decisive against any particular view of the determinants of choice behavior. The pro-

Table 3

Choices of green and red on the first response after reinforcement, subdivided according to the immediately preceding reinforcement, during the final 10 sessions of Exp. 2.

Bird No.	Preceding reinforcement	First response		Proportion of responses to green	
		Green	Red	Subdivided	Pooled
58	Green	253	92	0.73	0.73
	Red	71	27	0.72	
59	Green	298	101	0.75	0.74
	Red	63	28	0.69	
60	Green	292	85	0.78	0.74
	Red	68	43	0.61	

cedure of Exp. 1 differed in many ways from Shimp's procedure, and further research on the parameters of choice experiments will be needed to elucidate those conditions which favor the development of control by various aspects of concurrent-schedule contingencies. The present results merely indicate that conformity to certain aspects of the reinforcement contingencies is not a necessary condition for matching.

On the positive side, Exp. 1 suggested that choices conformed better to changes in the relative frequency of reinforcement than to changes in the probability of reinforcement within sequences of trials between reinforcements. This finding accords with a number of studies that have identified frequency or relative frequency of reinforcement as prepotent over probability of reinforcement in the determination of responding. For example, Anger (1956) analyzed the distribution of interresponse times obtained after extended exposure to variable-interval reinforcement. He demonstrated that the conditional probability of responding at different post-response times covaried with the obtained relative frequencies of reinforcement and not with the probabilities of reinforcement at those times. In a study of performance on concurrent chained schedules, Herrnstein (1964) found that the relative frequency of reinforcement in a terminal link was a better predictor of choices in the initial link than the relative probability of reinforcement. Neuringer and Schneider (1968) studied performance in a single-response, discrete-trial procedure and found that post-reinforcement latencies were controlled by the frequency of reinforcement and not by the probability of reinforcement.

The findings of Exp. 2 are related to earlier work on discrete-trial simultaneous discriminations by Nevin (1967). In one of his experiments, reinforcement was available for pecking the brighter of two keys after a fixed number of trials in a fashion analogous to the schedule in Exp. 2. Under these conditions, the probability of responding increased with successive trials after reinforcement, but the probability of choosing the brighter key remained constant. Final performance in the present Exp. 2 was approximately the same in these respects. Thus, performances in conventional simultaneous discrimination experiments and concurrent-schedule experiments which provide

reinforcement for both alternatives may be functionally similar.

This last possibility is brought into question by the present extinction data. Nevin (1967) found that the probability of pecking the brighter key did not change during experimental extinction, although the probability of responding decreased systematically. In Exp. 1, the probability of responding decreased in much the same way during the 10 sessions of extinction, and the probability of choosing green rather than red decreased at the same time to about 0.50. There is a fair amount of data from various situations indicating invariance during extinction in choices of a stimulus formerly correlated with reinforcement (e.g., Cumming *et al.* 1967; Zeiler, 1968). It remains to be determined whether manipulation of the parameters of concurrent-reinforcement procedures will also lead to invariance in choice data during extinction.

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