JOURNAL OF THE EXPERIMENTAL ANALYSIS OF BEHAVIOR 1969, 12, 403-411 NUMBER 3 (MAY)

THE CONCURRENT REINFORCEMENT OF TWO INTERRESPONSE TIMES: THE RELATIVE FREQUENCY OF AN INTERRESPONSE TIME EQUALS ITS RELATIVE HARMONIC LENGTH[1]

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The relative lengths of two concurrently reinforced interresponse times were varied in an experiment in which three pigeons obtained food by pecking on a single key. Visual discriminative stimuli accompanied the two time intervals in which reinforcements were scheduled according to a one-minute variable-interval. The steady-state relative frequency of an interresponse time approximately equalled the complement of its relative length, that is, its relative harmonic length. Thus, lengths of interresponse times and delays of reinforcement have the same effect on the relative frequencies of interresponse times and choices in one-key and two-key concurrent variable-interval schedules, respectively. A second experiment generalized further the functional equivalence between the effects of these one-key and two-key concurrent schedules by revealing that the usual matching-to-relative-immediacy in two-key concurrent schedules is undisturbed if reinforcement depends upon the occurrence of a response at the end of the delay interval, as it does in the one-key schedules. The results of both experiments are consistent with a quantitative theory of concurrent operant behavior.

A recent experiment demonstrated a functional similarity between delay of reinforcement and interresponse-time (IRT) length (Shimp, 1968). Specifically, for one pair of concurrently reinforced IRTs (2 sec and 4 sec), the relative frequency of the 2-sec IRT equalled 0.699 and therefore approximately equalled the complement of its relative length, *i.e.*, $1 - [2/(2 + 4)] = 0.667$. Such an equality would be predicted if the length of an IRT had the same effect on its relative frequency, in one-key concurrent variable-interval schedules, as the length of a reinforcement delay for one of several choices has on its relative frequency in two-key concurrent variable-interval schedules (Chung and Herrnstein, 1967).

The generality of this functional similarity could not be fully assessed in the previous study because only one pair of concurrent IRTs was used. The present study was designed to explore the generality of this similarity between the effects of reinforcement delays and IRT lengths. We asked if the above approximate equality was merely a coincidence, true only at 0.667, or if it was actually one point on a matching function such as the one obtained by Chung and Herrnstein. In other words, does an interresponse time x-sec long have the properties of an x-sec delay of reinforcement?

EXPERIMENT I

METHOD

Subjects

Three experimentally naive male homing pigeons served.

Apparatus

The right key in a Lehigh Valley Electronics two-key pigeon chamber was used. Standard commercial apparatus was used to schedule reinforcing contingencies and visual stimuli. Interresponse times were recorded on electromechanical counters and on a digital printer (Lehigh Valley Electronics #16609).

Procedure

The procedure was closely similar to that of the previous study. In particular, two dis-

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[1] This research was supported in part by a grant from the University Research Committee of the University of Utah. The writer would like to thank Mr. Wallace Cooper and Mr. Larry Hawkes for running the subjects in Exp. I, Mr. John Malouf for running the subjects in Exp. II, and Miss Barbara White for helping with the data analysis. In addition, the writer is indebted to Dr. Charles N. Uhl who provided, through NIMH grant #13904-01, the equipment used in Exp. II. Reprints may be obtained from the author, Dept. of Psychology, University of Utah, Salt Lake City, Utah 84112.

criminated IRTs were concurrently reinforced, and the relative frequency of reinforcement (π) was experimentally controlled. Previously, the lengths of the two IRTs were fixed; here, their lengths were varied over the experimental conditions.

Stimuli

Figure 1 shows the sequence of stimuli that transilluminated the response key. The two stimuli were the colors red and green. The key was darkened between the two stimuli to help reduce the frequency of responses when the red or green stimuli were not present. The key was lighted after the second stimulus to prevent the pigeon from roosting, which could have happened because there was no houselight. As can be seen in Table 1, red was the first color in some conditions and green was first in others. As explained below, the various time intervals, *i.e.*, between stimuli and durations of red and green, were varied over conditions. The key was dark during reinforcement, after which the sequence of stimuli started over as in Fig. 1.

Reinforcing Contingencies

In the variable-interval schedule of reinforcement used, the reinforcements-per-opportunity (Catania and Reynolds, 1968) were approximately constant at 0.1 every 8.2 sec, except at long times after reinforcement. The punched tape had 34 interreinforcement intervals and the average interval was 1.0 min. Otherwise, reinforcements were scheduled exactly as in the earlier study. That is, when a reinforcement was assigned by the punched tape, it stopped until the reinforcement was delivered. If a reinforcement became available for a peck in, for example, red, then pecks in green went unreinforced until the reinforcement of a peck in red enabled the tape to move again. Only responses terminating IRTs in red or green were reinforced. In summary, after a reinforcement became available, it was delivered for a response in the presence of either red or green, it was never simultaneously available for both stimuli at once, and it had to be collected before the next assignment could be made. The two reinforcing events followed a random sequence. That is, the sequence was a sequence of Bernoulli trials with $p = 0.5$. The relative frequency of reinforcements for response in red equals the number of reinforcements for responses in red divided by the sum of the number of reinforcements for responses in red plus the number of reinforcements for responses in green. This relative frequency is denoted by π. It equals the relative time rate of reinforcement for responses in red and, since p was 0.5, it equalled 0.5 except for sampling fluctuations. Thus, an advantage of the present method of scheduling reinforcements is that the obtained relative frequency of reinforcements equalled the scheduled relative frequency, so long as a bird responded at least occasionally to both stimuli. That is, the relative frequency of reinforcement was controlled mainly by the experimenter: within broad limits, a bird's behavior did not affect it. Feeder times were 2 sec for both IRTs so that the relative magnitude of reinforcement (F) was also constant throughout the experiment.

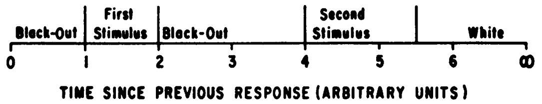

Fig. 1. Sequence of stimuli presented on the translucent response key as a function of the time since the last response. The durations of the stimuli and the between-stimuli durations varied across conditions.

Recording

Interresponse times were recorded in each session with eight electromechanical counters that gave only a crude estimate of the IRT distribution. Of the eight counters, two gave the frequencies of responses in red and green. On the last day of each condition, IRTs longer than a minimum depending on the condition, were recorded to the nearest 0.09 sec on the digital printer. Unlike the earlier study, here latencies after reinforcements were recorded. Every response preceding the third reinforcement was discarded to avoid recording warm-up effects.

Training and Experimental Conditions

The sequence of experimental conditions is shown in Table 1. While the conditions differed primarily in the lengths of the two reinforced classes of IRTs, there were also slight differences in the widths of the reinforced classes. These latter differences were attributable indirectly to the greater dispersion in IRT distributions with longer means (*e.g.*, see Shimp, 1967). The greater

Table 1

Experimental Conditions

Condition #	*Reinforced IRTs (Sec) (Short, Long)*	*Stimulus Sequence (Short, Long)*	*Relative Harmonic Length of the IRT Associated with the Red Stimulus*	*Number of Days*
1	(1.43-2.43, 3.43-4.43)	(Red, Green)	0.682	41[1]
2	(1.43-2.43, 4.93-5.93)	(Red, Green)	0.749	14
3	(1.43-2.43, 7.93-8.93)	(Red, Green)	0.823	14
4	(1.43-2.43, 12.93-15.43)	(Red, Green)	0.887	21[2]
5	(3.38-4.18, 4.48-6.28)	(Red, Green)	0.584	10
6	(3.68-4.68, 5.68-7.18)	(Green, Red)	0.394	10
7	(3.68-5.18, 15.68-18.18)	(Green, Red)	0.204	10
8	(3.68-5.18, 25.68-28.18)	(Green, Red)	0.138	11[3]
9	(3.68-4.68, 5.28-6.78)	(Green, Red)	0.409	13

[1] Thirty-two for Bird 8.

[2] See procedure for the different stimulus durations used early in this condition.

[3] Ten for Bird 8.

dispersion tended to reduce the proportion of responses falling within the reinforced portion of the longer of the two IRT distributions. The greater dispersion reduced absolute reinforcement rates in the early sessions of Condition 4. To avoid contamination by the effects of absolute reinforcement rate, the width of some of the longer reinforced classes was increased, beginning with Condition 4, as shown in Table 1. The large number of sessions in Condition 4 was due to the widening of the longer reinforced class from 1.0 sec to 1.5 sec and finally to 2.5 sec, beginning in Session 15.

Each experimental session lasted 50 min.

RESULTS

The appropriate independent variable for Exp. I is suggested by Killeen's (1968) interpretation of the independent variable in Chung and Herrnstein's experiment. Killeen argued that the harmonic mean often is a better measure of central tendency than the arithmetic mean. The relative immediacy of one of two delays of reinforcement, which was the independent variable in Chung and Herrnstein's experiment, is the same as the relative harmonic length of that delay. Two implications follow for Exp. I. First, the independent variable should be the relative harmonic length of one of the IRTs (either red or green), and second, the harmonic length of an IRT should be in terms of the harmonic mean of the end-points of the reinforced interval, not the arithmetic mean. For example, the value of the independent variable for Condition 1, *i.e.*, the relative harmonic length of the IRT associated with a red stimulus, equals

$$\frac{\frac{1}{2}\left(\frac{1}{1.43}+\frac{1}{2.43}\right)}{\frac{1}{2}\left(\frac{1}{1.43}+\frac{1}{2.43}\right)+\frac{1}{2}\left(\frac{1}{3.43}+\frac{1}{4.43}\right)}.$$

These values for each condition are shown in Table 1. It may be noted that these values differ negligibly from those based on the arithmetic means, rather than on the harmonic means, of the end-points of the reinforced intervals. For no condition do the two relative harmonic lengths differ by more than 0.025.

As with the independent variable, there is more than one possible dependent variable. Originally, the writer planned to follow a method similar to that of his previous experiment on concurrent IRTs; that is, to construct IRT distributions from the digital-printer records obtained on the last day of each condition and to determine by inspection the IRTs associated with red and green stimuli but not occurring in their presence. However, the narrow bin-width of 0.09 sec emphasized irregularities just where ambiguity was most troublesome for determining end-points of distributions—at the tails of the distributions. Furthermore, unlike the previous experiment where the reinforced IRTs were constant, here the shifting positions of the reinforced IRTs precluded a single definition for either a "short" or a "long" IRT. The resulting definitions thus acquired an excessively arbitrary character. Also, the greater resolution given by the present bin-width of 0.09 sec, as opposed to the previous 0.5 sec, revealed no new, interesting phenomena. Furthermore, preliminary analyses based on arbitrary definitions of "short" and "long" did not change the findings discussed below. For these reasons, the method of the earlier experiment was abandoned in favor of a simpler, more straightforward one: only responses terminating in the presence of red or green stimuli were considered, and the dependent variable was defined as the relative frequency of responses terminating IRTs in the presence of the red stimulus. The four panels in Fig. 2 show the resulting relative frequencies from each of the last two days for each condition and for each bird, and the averages of these individual data points. The numbers of responses in red or green over the last two days of each condition are shown in Table 2, along with the relative frequencies of responses in either red or green compared to total responses. Figure 2 also shows the least-squares, best-fitting straight lines to the averaged data. It can be seen that the data for Bird 9 very closely resemble the matching function. The data for Birds 7 and 8 resemble matching less closely, but certainly reveal that the relative length of an IRT affects its relative frequency. Furthermore, the deviations from matching appear fairly orderly; that is, the deviations for Birds 7 and 8 may be described as biases in favor of the first stimulus and of the green stimulus, respectively. The averaged curve is quite close to the matching function. The matching obtained here appears to be about as good as in Chung and Herrnstein's experiment. Even though the average curve is very close, individual differences make individual predictions hazardous.

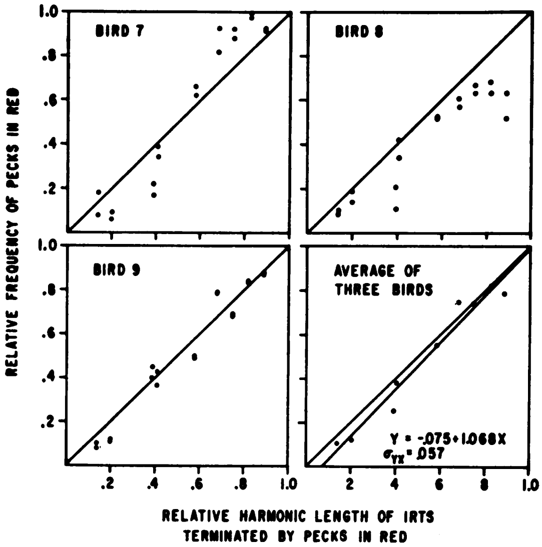

Fig. 2. The relative frequency of responses terminating an interresponse time in the presence of a red stimulus as a function of the relative harmonic length of that interresponse time. The solid lines are the matching functions. The second line in the lower right panel is the least-squares best-fitting straight line. The relative frequency of a red interresponse time approximately equals its relative harmonic length.

Table 2

Frequency of response in red or green on last two days (and relative frequency of these responses compared to total responses).

	Frequency in Red or Green		
Condition	*Bird 7*	*Bird 8*	*Bird 9*
1	1593 (0.74)	1125 (0.80)	1578 (0.75)
2	1421 (0.73)	1006 (0.78)	869 (0.70)
3	895 (0.50)	639 (0.78)	1079 (0.76)
4	750 (0.47)	533 (0.81)	1071 (0.82)
5	637 (0.56)	763 (0.86)	805 (0.79)
6	600 (0.53)	530 (0.60)	640 (0.61)
7	574 (0.64)	673 (0.92)	735 (0.88)
8	560 (0.80)	516 (0.89)	708 (0.89)
9	441 (0.29)	540 (0.62)	928 (0.86)

DISCUSSION

The results of Exp. I extend the generality of the functional similarity found previously between delay of reinforcement and IRT length in concurrent variable-interval schedules. The results show that the previous similarity was more than coincidental: the relative frequency of an IRT does in fact approximately equal the complement of its relative length when relative frequency and relative magnitude of reinforcement are equal. The present data therefore confirm the "matching point" conjecture common to both combination rules previously suggested for concurrent IRTs (Shimp, 1968). In short, the matching function heretofore found only in two-key choice data is now generalized to one-key IRT data.

The obtained functional similarity between choices and IRTs might itself seem less coincidental and more meaningful if it were not that reinforcement immediately followed a response in Exp. I but followed a response only after some interval of time in Chung and

Herrnstein's experiment. Thus, it might seem that this difference in response-reinforcement contingencies would preclude a profitable analogy between IRT length and delay of reinforcement. Experiment II was designed to explore the importance of this difference between response-reinforcement contingencies. Specifically, in Exp. II, what are presumably the essentials of the procedure of Chung and Herrnstein were replicated, except that reinforcement immediately followed a response made at the end of the delay interval.

EXPERIMENT II

METHOD

Subjects

Three male homing pigeons, with diverse experimental histories, served.

Apparatus

Two pigeon keys, similar to those from Lehigh Valley Electronics, were mounted in a standard experimental space.

Procedure

The procedure replicated a portion of Chung and Herrnstein's (1967) in all but the one respect mentioned above. That is, the procedures were the same in that reinforcements on the different keys were scheduled according to different, independent, variable-interval schedules with average IRT intervals of 1 min. A 1-sec changeover delay was scheduled. Normally, both keys were white. The first response on a key, after a reinforcement was assigned on that key, turned off both key lights and initiated a black-out delay. There was no houselight. During a black-out, and also during a reinforcement, both reinforcement programmers were stopped. As distinct from the procedure used by Chung and Herrnstein, here the feeder was not automatically presented at the termination of a black-out. Instead, both keys were lighted and the first response on the key on which a response had initiated the black-out was reinforced. Thus, reinforcements immediately followed a response. The key lights were darkened for approximately 40 msec after every response in an attempt to stabilize response topography.

Table 3 shows the experimental conditions, which differed only by the lengths of the black-out delays. Each session was 50-min long and a reinforcement consisted of access to food for 2 sec.

Table 3

Experimental Conditions

Length of Black-Out (Seconds)		*Number of Days*
Left key	Right key	
2	2	10
2	8	17
20	8	34

RESULTS

The dependent variable in Exp. II was the relative frequency of responses on the left key, that is, the number of responses on the left key divided by the total number of responses. The data reported are averages over the last two days of each condition, and exclude the very few responses made during black-outs. The independent variable was the relative immediacy of reinforcement for responses on the left key, that is, the complement of the relative delay. The relative delay was independent of the pigeons' behavior in the experiment by Chung and Herrnstein. However, in the present experiment, this delay depended partly on a subject: that is, it depended on the latency between termination of a black-out and the reinforced response. The time between the choice response initiating the black-out and reinforcement includes this latency. The average latencies are shown in Table 4. The procedure allowed a response to the non-reinforced key after a black-out terminated. The latencies shown in Table 4 include this time spent in pecking the wrong key after a black-out and before switching and receiving reinforcement. These responses were not separately recorded because casual observation revealed them to be infrequent. The latencies were not recorded for Condition 1, so an uncorrected relative immediacy of 0.50 is used

Table 4

Average latencies (sec) from end of black-out to reinforcement.

	Bird 1		*Bird 2*		*Bird 3*	
Condition	*Left*	*Right*	*Left*	*Right*	*Left*	*Right*
2	1.3	2.0	1.8	4.1	1.0	2.5
3	3.1	3.8	4.5	6.2	8.8	2.8

there. The corrected relative immediacies appear as the x co-ordinates of the points in the left panel of Fig. 3, which shows the three individual birds' data. Also shown in Fig. 3 are the ranges of the relative frequencies from Chung and Herrnstein's four birds in the conditions with delays 2 sec and 8 sec, 8 sec and 8 sec, and 20 sec and 8 sec. The left panel shows that only one of nine data points falls outside the range of values obtained by Chung and Herrnstein for corresponding conditions. The single exception is barely outside the range of the earlier data. The right panel shows the averaged x and y co-ordinates of the data in the left panel. The averages from the two experiments are virtually identical.

It may be concluded that whether or not a response is required at the end of the black-out is immaterial in two-key concurrent variable-interval schedules. That is, matching is obtained for both response-reinforcement contingencies.

DISCUSSION

Experiment I demonstrated matching in a one-key concurrent variable-interval schedule, and this behavior is reminiscent of the matching obtained by Chung and Herrnstein in a two-key concurrent variable-interval schedule. In both experiments, the relative frequency of one of two operants matched a temporal variable, measured in terms of either black-outs or IRTs. However, a difference between response-reinforcement contingencies does exist between the one-key and two-key experiments. That is, reinforcement was presented automatically at the end of a black-out in Chung and Herrnstein's experiment, and thus followed the preceding response by a time exactly equal to the black-out. But in Exp. I, reinforcement was presented immediately after a response terminating an IRT. However, Exp. II showed that the two-key data are unaffected if reinforcement is immediate for a response at the end of the black-out. Therefore, the difference in contingencies apparently does not affect the similarity between the effects of black-out duration in the two-key schedule and the effects of IRT length in the one-key schedule. In brief, Exp. I and II together reveal a functional equivalence between concurrently reinforced IRTs on a single key and concurrently reinforced pecks on different keys.

The demonstrated functional equivalence

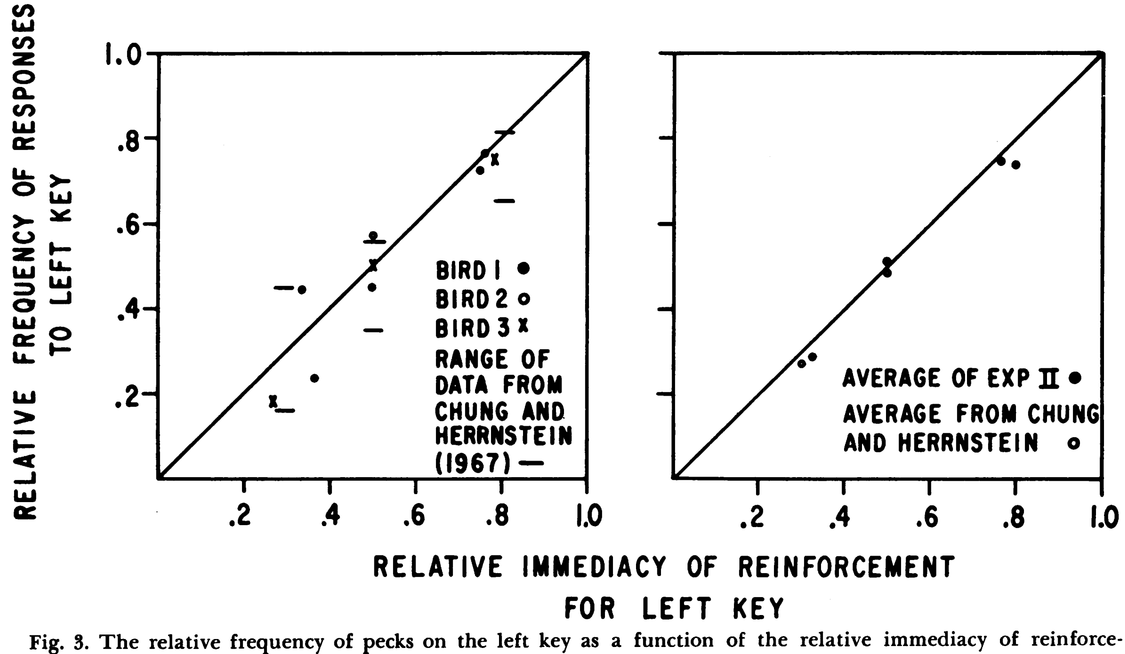

Fig. 3. The relative frequency of pecks on the left key as a function of the relative immediacy of reinforcement for pecks on that key. The left panel compares the individual data of three birds with the ranges (short horizontal lines) obtained earlier by Chung and Herrnstein for corresponding conditions. The right panel compares the means from the present experiment with those of Chung and Herrnstein's experiment. Both experiments produced matching.

permits an interesting analogy between sequences of events in Exp. I and in Exp. II. First, the events in Chung and Herrnstein's experiment can be summarized as follows: a choice of two keys is possibly followed by a black-out and reinforcement. From Exp. II we know that this sequence has the same effect on the relative frequency of a choice as the following sequence: a choice of one of two keys is possibly followed by a black-out, after which a bird responds and produces reinforcement. Now Exp. I shows that black-out length is functionally equivalent to IRT length, so the following sequence may be inferred for the concurrent IRT schedule: a choice of one of two IRTs is followed by the interval, after which a bird responds and produces reinforcement. Two differences are immediately apparent between the sequences for the experiment by Chung and Herrnstein and for Exp. I. First, according to the above sequences of events, in their experiment a choice was between two alternative keys; but in Exp. I, a choice was between two alternative IRTs. Since the choice precedes the following interval, the inferred sequence suggests that the length of an IRT is determined at its beginning. Second, in the Chung and Herrnstein experiment, only reinforced responses preceded black-outs, whereas in Exp. I, all but reinforced responses preceded an IRT interval. These two differences will be discussed in order.

Arguments suggesting that the length of an IRT is determined at its beginning are not common. The above argument can probably be viewed in better perspective by comparing it with two other alternatives. Perhaps the single most common alternative viewpoint is that the length of an IRT is determined at its termination. This assumption often seems implicitly made when an author transforms a relative frequency distribution to a conditional (an interresponse-times-per-opportunity) distribution. In fact, the issue at stake can be rephrased as "which of the two distributions, relative frequencies or conditional frequencies, is the more direct measure of behavioral processes?" The sequence of events inferred above implies that the relative frequency distribution is more direct, while a "go, no-go" assumption implies that the conditional frequency distribution is more direct. A go, no-go assumption for free-operant IRTs is supported by data collected by Mueller (1950) and by Anger (1956). (Of course there is no guarantee that free-operant IRTs behave like the IRTs in the present experiment, but discriminated IRT data that unambiguously support a go, no-go assumption are lacking. Thus, for the sake of the go, no-go argument, these free-operant IRT are cited). These experimenters discovered flat interresponse-times-per-opportunity curves at the very beginning of training, presumably before the various reinforcing contingencies began to control behavior. Such a curve is easily described by assuming first that a bird chooses from among the two alternatives "go" (peck) or "no-go" (do not peck), so that the length of an IRT would be determined at its termination, and by assuming secondly that the probability of "go" is constant. A flat interresponse-times-per-opportunity curve generates an exponential IRT distribution. There would seem to be no particular reason to expect such a distribution if IRTs were determined at their beginnings. In fact, a flat IRT distribution might then be expected. While the initial behavior reported by Mueller and Anger may therefore be described better by a go, no-go sequence, than by the sequence inferred for Exp. I, steady-state behavior presents a more difficult problem for a go, no-go sequence. Take, for example, the schedule in Exp. I and assume a go, no-go sequence of events. The probability of a response simply would equal some number when red appeared and another, perhaps the same, number when green appeared. As a result, the natural prediction would be that the relative frequency of an IRT would not depend on its relative length. There would simply be some probability that when a stimulus came on, a bird would respond. There is nothing in the nature of a go, no-go sequence to suggest that the relative frequency of pecks in red would depend on when green appeared. In particular, it is unclear how a go, no-go interpretation of Exp. I could predict matching except on an unsatisfactory *ad hoc* basis. For example, it might be assumed that the probability of a "go" in red or green changes from condition to condition. But it is unclear how these changes might be predicted independently from, or even be related to, other data in the literature. In short, a go, no-go description of Exp. I is not parsimonious compared to the description in which an IRT is determined at its beginning.

While a go, no-go process by itself would not seem to describe the present data, such a process may be combined with another so that the resulting process can describe the data. The two kinds of processes described so far may be discriminated by noting whether the length of an IRT is determined at its termination (the go, no-go view) or before (*e.g.*, at its beginning). These two kinds of processes may be combined in the following way. Let there be one choice point, but let it be in S_1 rather than at the beginning of the sequence in Fig. 1. Then, a response in S_1 implies a choice of the short IRT. The short IRT is therefore determined at its termination and is described by the "go" component of a go, no-go process. Under the assumption that there is but one choice point, a non-response (a no-go) in S_1 will imply a choice of the long IRT. The long IRT is therefore determined before its termination and therefore not described by a go, no-go process. According to this idea, the relative frequency of an IRT would match the relative harmonic length of the delay from the time of its choice to the next possible moment of choice. For instance, if short and long IRTs were 2 sec and 5 sec, the delay from choosing the 2-sec IRT (at its termination) to the next moment of choice would be 2 sec. The delay from choosing the 5 sec IRT (sometime during S_1, for example at 2 sec) would be the 3 sec between the choice at 2 sec and the response terminating the 5-sec IRT plus the 2 sec between the terminated 5-sec IRT and the next possible choice point at 2 sec. That is, the delay would be 2 sec plus 3 sec, or 5 sec. Thus, this combined process leads to the same independent variable as the assumption that an IRT is determined at its beginning. Therefore, it must be concluded that at least two processes could account for the present IRT matching behavior.

If there are two potential accounts for the present behavior, is there any way, at present, to choose conclusively between them? The following summary suggests that probably there is not. The viewpoint that an IRT is determined at its beginning describes both short and long IRTs in similar terms and is in that sense more parsimonious than the viewpoint that the short IRT is determined at its termination but the long IRT is determined before its termination. However, the choice in the former case is not directly observable at the moment at which it is assumed to occur, whereas in the latter, it is. Thus, the present data cannot discriminate between the two accounts: which one seems preferable clearly depends on personal taste.

The second difference between the sequences of events for the experiment by Chung and Herrnstein and for Exp. I is the percentage of responses followed by a black-out or by an IRT. The present description predicts that if every choice in a Chung and Herrnstein-type schedule initiated a black-out (only some of which would end in reinforcement), matching would still be obtained. Further research is needed to test this prediction.

The data presented here support a quantitative, descriptive theory of concurrent operant behavior (Shimp, in press). The gist of this theory is, briefly, that many of the gross features of concurrent operant behavior may be predicted from the assumption that the operant most likely to be emitted is that which maximizes the weighted probability of reinforcement. For the schedule in Exp. I, the momentary reinforcement probabilities are weighted, according to the theory, by a curvilinear function of the IRT lengths. The present data support this theory in three ways. First, the theory assumes that IRTs are determined at their beginnings. As shown above, these data are consistent with this assumption. Second, the theory predicts the obtained matching behavior, and does so *a priori* since the present experiment is, in terms of the theory, identical to Chung and Herrnstein's and the theory predicts the matching obtained there. The theory also describes why the response-reinforcement contingency between Exp. II and Chung and Herrnstein's experiment makes no difference. The only importance of a black-out is as a determiner of the weighted reinforcement probability. The difference in contingencies does not alter this effect of the black-outs.

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Received 9 August 1968.