THE CONCURRENT REINFORCEMENT OF TWO INTERRESPONSE TIMES: ABSOLUTE RATE OF REINFORCEMENT¹

CHARLES P. SHIMP

UNIVERSITY OF UTAH

Three pigeons obtained food on a one-key schedule of reinforcement for two concurrent, discriminated interresponse times. The overall rate of reinforcement was determined by a family of variable-interval schedules and by a continuous reinforcement schedule. The average frequency of reinforcement varied from 1.1 to 300 reinforcements per hour; the relative frequency of reinforcement for each of the two interresponse times was 0.5 throughout the experiment. The number of responses per minute increased sharply as the number of reinforcements per hour increased from 1 to 20. Beyond 30 reinforcements per hour, the curve was approximately flat, although it sometimes decreased slightly at the highest reinforcement rates. The relative frequency of the shorter interresponse time also increased sharply as the number of reinforcements per hour increased from 1 to 20. The asymptote of the relative frequency function approximately equalled the relative reciprocal of the length of the shorter interresponse time for reinforcement rates greater than 30 or 40 reinforcements per hour. This approximation was obscured by the response-rate function.

Two recent studies sought to identify the functional relationship between the relative frequency of reinforcement for one of two concurrent operants and the relative frequency of occurrence of that operant, when the two operants are interresponse times (Shimp, 1968; Staddon, 1968). A third experiment revealed that this functional relationship depends on the relative lengths of the two interresponse times (Shimp, 1969). In these three experiments, the absolute rate of reinforcement varied from approximately 40 to 100 reinforcements per hour. As is well known, reinforcement rate often affects response rate (see, for example, Catania and Reynolds, 1968). While the number of responses emitted per unit time in concurrent interresponse-time schedules and the response rate in classical free-operant schedules may not share all the same properties, nevertheless they might share a dependency on reinforcement rate. And in experiments on the reinforcement of two concurrent interresponse times, a change in the number of responses emitted per unit time might change

the relative frequencies of the two interresponse times. Consequently, rate of reinforcement may be a second variable, like the relative lengths of the two interresponse times, that modulates the dependency between the relative frequency of reinforcement for an interresponse time and the relative frequency of its occurrence. If the dependency were in fact modulated in this way, the functions previously suggested by Shimp (1968) and by Staddon (1968) to describe it would apply only to restricted reinforcement rates. The present experiment was designed to investigate this possibility.

METHOD

Subjects

Three experimentally naive homing pigeons were maintained at 80% of their free-feeding body weights.

Apparatus

The right-hand key in a Lehigh Valley Electronics two-key pigeon chamber was used. Commercial relay apparatus arranged the several contingencies and the presentation of visual stimuli.

Procedure

The procedure was virtually identical to that of previous experiments in this series on

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the reinforcement of concurrent interresponse times (Shimp, 1968, 1969). Two discriminated interresponse times (IRTs) were concurrently reinforced while both relative frequency of reinforcement (π) and relative magnitude of reinforcement (F) were equal to 0.5. In the present experiment, only the overall frequency of reinforcement was varied.

Stimuli. The sequence of stimuli, which was cycled by a response, and which appeared on a transilluminated response key, is shown in Fig. 1. There was no houselight. It should be noted that the response terminating an IRT could occur during a black-out, or during a red or a green stimulus.

Fig. 1. The sequence of stimuli appearing on the translucent key as a function of time-since-last-response.

Reinforcement contingencies. As in the two earlier studies, the distribution of reinforcements in time was determined by a variable-interval schedule, and the distribution of reinforcements for the two IRTs was determined by a Bernoulli-trials generator. That is, the probability, p , that the generator would assign a reinforcement to the shorter IRT was independent of the preceding assignment and was constant over assignments. In the previous studies, the variable-interval schedule was held constant, whereas in the present experiment, the rate of reinforcement provided by the variable-interval schedule was the independent variable.

A variable-interval schedule was constructed for which the "reinforcements per opportunity" was approximately constant at 0.1 every t sec (Catania and Reynolds, 1968). Five values of t were calculated to provide schedules with average interreinforcement intervals of 20 sec, 30 sec, 60 sec, 3 min, and 6 min. The 6-min tape consisted of 20 intervals and each of the other four tapes consisted of 34 intervals. In addition, two variable-interval schedules, with average interreinforcement intervals of 12 min and 18 min, were obtained by covering over holes in the 6-min tape in a semi-random fashion. A continuous reinforcement condition was arranged by replacing the variable-interval component of the reinforcement contin-

gencies with a continuous reinforcement schedule so that, as explained below, the scheduling of a reinforcement depended only on the Bernoulli-trials process.

The punched tape and the Bernoulli-trials generator together assigned reinforcements in the following way. When the tape assigned a reinforcement, it halted and a Bernoulli trial determined whether that reinforcement would be assigned to the shorter IRT or to the longer. The resulting contingency remained in effect until the appropriate IRT was terminated, food was presented, and the tape began to move again.

The relative frequency of reinforcement was independent of a subject's behavior; it was entirely dependent on the outcomes of the Bernoulli trials and in no way was affected by the relative frequencies of the IRTs. The parameter p in the Bernoulli-trials process was 0.5 throughout the present experiment and so the relative frequency of reinforcement for either IRT equalled 0.5, except for sampling fluctuations. The feeder time was equal to 2.0 sec for each IRT.

Recording. Interresponse times were recorded during each session with eight electromechanical counters that provided a rough estimate of the IRT distribution. Two of these counters counted the number of IRTs in the presence of the red or green stimuli. On the last two days of each condition, IRTs longer than a minimum of 0.5 sec were recorded to the nearest 0.09 sec by the use of a digital printer.

Training and experimental conditions. The sequence of experimental conditions and the durations of the experimental sessions are shown in Table 1. The session duration was lengthened in conditions with low reinforcement rates in an attempt to have each bird receive at least one food presentation per session. It was shortened in conditions with high reinforcement rates to prevent the birds' body weights from exceeding 80% of their free-feeding weights. Subjects were run seven days a week, and experimental conditions were terminated when behavior had appeared stable for three or four days.

RESULTS

Both the independent variable, *i.e.*, the absolute rate of reinforcement, and the depen-

Fig. 2. Representative interresponse-time distributions. Reinforcements were available only when the keylight was red or green.

dent variable, *i.e.*, the frequencies of the two concurrent IRTs, may be defined variously; therefore, they must be unambiguously specified before the results can be presented. The reinforcement rate may be plotted either as the scheduled or the obtained values. The latter are clearly preferable and are used here. For comparison, Table 1 shows both values for each condition.

Representative IRT distributions are helpful guides to determining the appropriate dependent variable. Figure 2 shows three IRT distributions representative of experimental conditions with high and low relative frequencies of IRTs in the presence of or near the red stimulus. From these distributions it can be

seen that the intervals during which a red, or a green, stimulus was present respectively define a shorter, or a longer IRT, and do so about as well as any single, fixed definition, for Birds 10 and 11. For Bird 12 in some conditions, this definition omits a considerable number of responses before the presentation of the red stimulus. However, for the sake of consistency, this definition is employed here even for Bird 12. The entries in the nine columns on the right in Table 1 show the frequencies of responses during red or green on each of the last two days of each condition. The percentages of all responses that occurred in the presence of the red or of the green stimulus are shown in Table 1.

Fig. 3. The number of responses in red or green per minute, corrected for feeder time, as a function of the obtained absolute rate of reinforcement. The "X"s and points over CRF are for Conditions 10 and 11, respectively.

Table 1

Condition No.	No. Days	Session Duration (min)	Scheduled Reinforcements per Hour	Obtained Reinforcements per Hour						Per cent of Responses That Were during Red or Green						Number of Responses during Red, during Green, and after Green on Each of the Last Two Days of Each Condition												
				Bird 10			Bird 11			Bird 12			Bird 10			Bird 11			Bird 12									
				R	G	>G	R	G	>G	R	G	>G	R	G	>G	R	G	>G	R	G	>G							
1	11	50	60	48	57	49	51	65	72	55	398	173	114	659	199	12	559	134	55	379	218	89	733	212	9	411	177	96
2	17	50	20	16	22	19	19	66	61	50	358	336	57	615	206	25	352	222	40	302	312	51	605	134	31	267	214	50
3	15	30	180	102	118	91	104	76	81	45	251	117	51	372	166	10	231	59	25	220	145	45	397	150	2	386	72	18
4	19	50	20	20	18	9	16	67	77	42	317	314	40	560	159	47	134	99	22	303	301	37	521	165	58	140	115	23
5	15 ¹	50	60	50	58	53	54	79	82	44	416	197	94	566	311	19	507	224	35	555	195	72	472	355	16	509	202	24
6	13	50	10	10	10	4	8	82	84	40	293	327	54	354	371	42	211	96	47	271	322	71	366	302	50	240	103	51
7	11	75	5	6	4	1	4	69	78	41	317	389	107	298	366	112	114	124	37	229	359	148	281	393	80	71	58	31
8	9	75	3.3	2	1	0 ²	1.1	69	76	50	160	319	44	218	168	36	103	55	37	154	268	47	120	134	34	92	45	23
9	12	35	120	84	81	87	84	71	76	48	135	242	76	421	84	74	283	139	35	128	178	106	372	102	73	298	105	56
10 ³	12	12 ⁴	(CRF)	171	300	185	219	63	85	49	30	63	35	77	40	13	58	34	49	27	39	25	40	32	6	101	26	27
11	6	9 ⁵	(CRF)	309	400	192	300	97	97	61	40	32	1	67	19	0	130	24	3	66	46	0	48	30	0	100	20	4

¹18 for Bird 10.²0.4 per hour.³Between Conditions 10 and 11, there were 4 sessions in which only responses in red were reinforced.⁴12 is the overall average for the three birds over the last two days. The average durations for Birds 10, 11, and 12 were 14, 8, and 13 min, respectively.⁵9 is the overall average for the three birds over the last two days. The average durations for Birds 10, 11, and 12 were 9, 6, and 12 min, respectively.

These two sets of definitions let the present data be examined in two ways. First, for comparison with earlier response-rate data (see, for example, Catania and Reynolds, 1968), Fig. 3 shows the total number of instances of either operant per minute, *i.e.*, the rate of emission of shorter or longer IRTs, plotted against the obtained reinforcement rate. The numbers were computed for individual subjects over each of the last two days of each condition and were corrected for reinforcement time. Each of the three panels of Fig. 3 showing individual data reveals an increasing function as the number of reinforcements per hour increases from 1 to 20. Beyond 30 or 40 reinforcements per hour, the slopes of the functions are negligible, with an indication of a slight decrease. This decrease is partly attributable to poor recoverability in two conditions, as explained below. These tendencies in the individual curves are clearly evident in the panel showing the averaged *x*- and *y*-co-ordinates of the three individual panels. Table 1 gives the numerical values of these averaged *x*-co-ordinates and the frequencies from which they were computed.

The second way to examine the data is to look at changes in the relative frequency of the shorter IRT. Notice that the two ways of examining the data may be independent. The response-rate method is affected by the time consumed by IRTs other than those terminated by responses in the presence of red or green. The IRT method is not so affected. The relative frequency of IRTs in the presence of red, *i.e.*, the number of IRTs in the presence of red divided by the total number of IRTs during red or green, was computed over each of the last two days of the different conditions. The ratios for the individual birds appear in three panels of Fig. 4. The fourth panel shows the averaged *x*- and *y*-coordinates of the three panels for the individual subjects. As in Fig. 3, the functions increase from 1 to 20 reinforcements per hour, and then are either approximately flat or they decrease slightly. The functions in Fig. 4 are less steep over the low reinforcement rates than are those as shown in Fig. 3.

The averaged function in the fourth panel of Fig. 4 appears to have an asymptote closely approximating the relative reciprocal of the length of the shorter IRTs, indicated by the dashed horizontal line at the value 0.681. The

relative reciprocal of the length of one of two IRTs is:

$$\frac{\frac{1}{t_{1,1}} + \frac{1}{t_{1,2}}}{\frac{1}{t_{1,1}} + \frac{1}{t_{1,2}} + \frac{1}{t_{2,1}} + \frac{1}{t_{2,2}}}$$

where $t_{1,1}$ and $t_{1,2}$ are the lower and upper bounds, respectively, of the i th class of reinforced IRTs. The average of the four data points about the dashed line is 0.696, which differs from 0.681 by only 0.015.

The continuous reinforcement condition would also appear, according to the points in Fig. 4, to agree very well with the matching value. However, this agreement is probably coincidental and not generally valid for other values of the relative reciprocal of the length of the shorter IRT. For continuous reinforcement, the relative frequency of the shorter IRT could easily depend upon an optimal strategy, which in this case could consist of a peck during red followed, if that peck were not reinforced, by a reinforced peck during green (see Shimp, 1966). Such behavior would produce here an overall relative frequency of responses during red of 0.67, independent of the relative reciprocal of the length of IRTs terminated during red.

The recoverability of data points in this experiment was generally good, with one exception. Figure 4 shows that, in Condition 9, when the average obtained rate of reinforcement was 84, Bird 10 failed to respond during red as often as would be predicted from the matching value or from the values previously obtained from that bird at reinforcement rates near 84 per hr. This failure probably was caused by the particular sequence of experimental conditions, in which Condition 9 was preceded by three conditions with extremely low reinforcement rates (10, 6, and 2 reinforcements per hour respectively, for Bird 10). In other words, after the subjects were run on these schedules, behavior consistent with that in earlier conditions was not recovered in the two conditions that followed, 9 and 10. The lack of recoverability was most severe for Bird 10, but was noticeable for each bird. Continuous reinforcement was given in Condition 10, and therefore, it was apparent that not even the highest possible reinforcement rate would be sufficient to recover behavior consistent with that in previous conditions. Therefore, special training was

Fig. 4. The relative frequency of shorter interresponse times as a function of the obtained absolute rate of reinforcement. The apparent asymptote of the group curve equals the relative reciprocal of the length of the shorter interresponse time. The "X"s and points over CRF are for Conditions 10 and 11, respectively.

given to all subjects to recover behavior more nearly like that predicted from maximizing in a continuous reinforcement schedule and from earlier behavior. The training consisted of four days of continuous reinforcement with $\pi = 1.0$ instead of 0.5. That is, all of the reinforcements were scheduled for pecks during red. Over the third and fourth days of this training, the relative frequencies of pecks during red were 0.86, 0.82, and 0.80 for Birds 10, 11, and 12, respectively. The procedure of experimental Condition 10 was then reinstated for five more days. That is, π was changed back to 0.5. These five days are called Condition 11. As shown by the points in Fig. 3 and 4 above

continuous reinforcement, the four interposed days with $\pi = 1.0$ raised the average relative frequency of pecks during red for $\pi = 0.50$ from 0.56 to 0.70. The latter figure is consistent with the data acquired before the conditions with very low rates of reinforcement.

DISCUSSION

The present experiment showed that a given relative frequency of reinforcement for an IRT does not produce the same frequency of occurrence of that IRT independently of the absolute rate of reinforcement. Two functions were obtained and both were curvilinear. Both

the rate of emission of two IRTs and the relative frequency of one of them increased sharply as the reinforcements per hour increased from 1 to 20, then, each levelled off and in some cases decreased slightly.

Low rates of reinforcement reduced the sum of the frequencies of the two IRTs proportionately more than they reduced the relative frequency of the shorter one. This comparison suggests that the response-rate function is a more sensitive effect of reinforcement rate. However, the relative-frequency function revealed a relationship wholly obscured by the response-rate function, namely, the near equality between the relative frequency of occurrence of an IRT and the relative reciprocal of its length (Shimp, 1969). Averaged over the four conditions with nearly constant effects (indicated by the dashed line in Fig. 4), the relative frequency of the shorter IRTs, 0.696, was quite close to the value of 0.681 predicted from earlier experiments (Shimp, 1968, 1969). While the asymptotic value agrees quite well with the matching value, the non-asymptotic values clearly show that matching can be only a special case. Matching appears to be limited to rates of reinforcement higher than approximately 30 or 40 reinforcements per hour and, perhaps, lower than some maximum reinforcement rate dependent upon the relative lengths of the IRTs (see the discussion of the continuous reinforcement condition in the Results section). The number of reinforcements per hour in Shimp (1968, 1969) ranged from approximately 23 to 69, and therefore was in the range required for approximate matching.

It is interesting to note that the matching phenomenon apparently does not depend on the use of discriminated IRTs, as in the present experiment and in Shimp (1968, 1969). The two reinforced classes of IRTs in the experiment by Staddon (1968) were not accompanied by discriminative stimuli. In his experiment, the shorter class of IRTs was from 2 to 3 sec, while the longer class was from 10 to 11 sec. According to the above formula, the relative reciprocal of the length of the shorter IRT was 0.81. The very useful Table 1 in his paper provides all the necessary data to determine whether matching was obtained. From it,

one may calculate that over his Conditions 9 and 11, the average relative frequency of reinforcement was 0.50 and therefore, if matching was obtained, the average relative frequency of the shorter IRT should equal 0.81. Again from his Table 1, it can be calculated that the average relative frequency of the shorter IRT was indeed 0.81. The matching phenomenon appears also to be independent of the definition of the two operants, since each of three different definitions can produce it. Originally, IRTs were defined as responses in the presence of, or just before, the discriminative stimuli (Shimp, 1968). In the present experiments, and in Shimp (1969), the operants were defined to be responses in the presence of the discriminative stimuli. Staddon (1968) did not use discriminative stimuli at all, included *all* IRTs in his definition, and placed the point defining the boundary between shorter and longer IRTs approximately midway between the two reinforced intervals. The matching phenomenon survives these changes in definition of the two concurrent operants.

This matching function and the present results show that two variables affect the relationship between the relative frequency of one of two concurrently reinforced IRTs and its relative frequency of reinforcement: its relative length and the rate of reinforcement.

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