

*SEQUENTIAL DEPENDENCIES IN FREE-RESPONDING*¹

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Three pigeons pecked for food in an experiment in which reinforcements were arranged for responses terminating sequences of interresponse times. Each reinforced interresponse time belonged to a class extending either from 1.0 to 2.0 sec (class A) or from 3.0 to 4.5 sec (class B). Reinforcements were arranged by a single variable-interval schedule and a random device that assigned each reinforcement to one of four sequences of two successive interresponse times: AA, AB, BA, or BB. Throughout the experiment, half of the reinforcements were delivered for interresponse times in class A and half for those in class B. Over conditions, the interresponse time preceding a reinforced interresponse time always, half of the time, or never, belonged to class A. The duration of the interresponse time preceding a reinforced one had a pronounced effect on response patterning. It also had a pronounced effect on the overall response probability, which was highest, intermediate, and lowest, when the interresponse time preceding a reinforced interresponse time always, half of the time, or never, belonged to class A, respectively. In no case were successive interresponse times independent, so that overall response probability was not representative of momentary response probabilities.

The nature of the relationship between response probability and response rate is a central issue in the analysis of free-responding. A plausible assumption is that response probability varies from moment to moment, thereby generating over time a distribution of response probabilities. Accordingly, a mean response rate may not estimate a single, constant, response probability, but may instead estimate the mean of a distribution of response probabilities. Two transformations of the frequency distribution of interresponse times (IRTs) have been proposed as estimates of this distribution of response probabilities: the relative-frequency distribution of IRTs, and the interresponse times per opportunity (IRTs/Op). It has been suggested that available data are not sufficient to determine which estimate is correct (Shimp, 1973). However, regardless of which estimate one uses, he apparently may conclude that response probability varies as a function of the time since the last response, even in, say, a constant-probability variable-

interval (VI) schedule that generates a straight-line cumulative record. That is, neither the relative-frequency distribution of IRTs nor the IRTs/Op is a constant function (Shimp, 1967).

Once it is established that response probability in a VI schedule depends on the time since the last response, the question arises of how this dependency arises. What variables determine the way in which response probability depends on the time since the last response? A number of controlling variables have been isolated and some of their quantitative effects have been mapped: the relative frequency of reinforcement for an IRT (Shimp, 1968, 1973; Staddon, 1968; Moffitt and Shimp, 1971); the relative magnitude of reinforcement for an IRT (Shimp, 1968; Moffitt and Shimp, 1971); the relative length of an IRT (Shimp, 1969b, 1973; Moffitt and Shimp, 1971); and, the total rate of reinforcement (Shimp, 1970).

The present experiment investigated the effect on response probability of the duration of the IRT preceding reinforced IRTs. Data from a wide variety of sources indicate that the function relating response probability to the time since the last response depends on the preceding IRT, that is, that the distribution of IRTs following one IRT is different from the distribution of IRTs following some

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other IRT (Angle, 1970; Blough, 1963, 1966; Blough and Blough, 1968; Ferraro, Schoenfeld, and Snapper, 1965; Kintsch, 1965, Weiss, 1970; Williams, 1968). The present experiment investigated whether this kind of sequential dependence can be controlled by the rate of reinforcement for different sequences of IRTs. The baseline schedule, a concurrent (*conc*) VI VI for two IRTs, was the same as that used previously to investigate variables controlling response probability as a function of the time since the last response.

METHOD

Subjects

Three White Carneaux pigeons were maintained at approximately 80% of their free-feeding weights. The subjects had extensive prior experimental training (see Herbert, 1970, and Experiment I in Moffitt and Shimp, 1971).

Apparatus

Only the center keys were used in three, three-key Lehigh Valley Electronics pigeon chambers. A Digital Equipment Corporation PDP-12 laboratory computer arranged all stimuli and reinforcements, and recorded data on magnetic tape for subsequent analysis.

Procedure

Variable-interval schedule. A single, constant-probability VI schedule arranged a reinforcement with probability 0.05 every 3.0 sec. The mean interreinforcement interval produced by the schedule therefore was 60 sec. (As described below, the actual rate of reinforcement was about one-half this value.) When a reinforcement was arranged, the VI timer stopped until the reinforcement was collected. No other reinforcement could be assigned until a previously arranged one was collected.

Reinforcement-selection mechanism. Each reinforcement arranged by the VI schedule was assigned by a random device to one of four sequences of two successive IRTs. The two classes of reinforced IRTs were those 1.0 to 2.0 sec in duration, and those 3.0 to 4.5 sec in duration. These two classes will be called classes A and B, respectively. It will be convenient to refer to the four sequences using the following notation: AA, AB, BA, and BB. The

notation is such that AB refers to a sequence in which an IRT in class A precedes an IRT in class B, etc. For example, if a subject pecked the key, waited 1.5 sec, pecked the key, waited 3.5 sec, and pecked the key, it would have emitted the sequence AB. The phrase "reinforced sequence" refers to a sequence, the terminal response of which is reinforced. When a reinforcement was assigned to a sequence, it remained assigned to that sequence and no new assignment could be made until that sequence was emitted and a reinforcer was collected.

The way in which reinforcements were allocated to these four sequences of two IRTs was varied. Specifically, the duration of the IRT preceding the reinforced one was varied, while throughout the experiment, IRTs in class A received half of the reinforcements and IRTs in class B received the other half. In condition A, an IRT preceding a reinforced IRT always belonged to class A. Thus, the reinforcement-selection mechanism randomly picked either AA or AB, so that the sequences AA and AB were reinforced equally often. In condition B, an IRT preceding a reinforced IRT always belonged to class B. Thus, the sequences BA and BB were reinforced equally often. In condition AB, an IRT preceding a reinforced IRT belonged to class A half of the time and to class B the other half of the time. Thus, all four sequences were reinforced equally often. Finally, in condition U, the duration of an IRT preceding a reinforced IRT was experimentally uncontrolled. Therefore, in condition U, reinforcements were arranged simply for IRTs belonging to class A or class B, and the schedule was an unmodified one-key *conc* VI VI schedule of reinforcement for two IRTs (Shimp, 1968). Only in condition U did the relative reinforcements per hour for the four sequences depend on a subject's behavior, although note that half of the reinforcements continued to be delivered for IRTs in class A and half of them were delivered for IRTs in class B. Table 1 summarizes the way in which reinforcements were allocated to the sequences and gives the duration of each condition.

Neither the first nor the second response after a reinforcement was ever reinforced. Three responses, appropriately spaced, were required to generate one of the four reinforced sequences, so that this restriction was equiva-

Table 1

Experimental Conditions

The name of an experimental condition is the name of the class, or classes, of IRTs preceding reinforced IRTs in that condition, except for condition U, where the IRT preceding a reinforced IRT was uncontrolled.

Order of Conditions	Number of Days	Programmed Relative Reinforcements Per Hour for the Four Sequences of Two Classes of Interresponse Times ¹			
		AA	AB	BA	BB
AB	28	0.25	0.25	0.25	0.25
B	20	0	0	0.50	0.50
A	23	0.50	0.50	0	0
AB	62	0.25	0.25	0.25	0.25
U	16		(Uncontrolled)		
B	20	0	0	0.50	0.50
U	12		(Uncontrolled)		

¹Class A extended from 1.0 to 2.0 sec and class B extended from 3.0 to 4.5 sec. The notation "AB" refers to a sequence in which an instance of class A preceded an instance of class B. Throughout the experiment, the programmed relative reinforcements per hour for IRTs in class A was 0.5.

lent to requiring a subject to generate a sequence of two IRTs that did not overlap the previously reinforced sequence.

An example of a sequence of IRTs that could be reinforced, should help to clarify the procedure. Consider condition AB, in which all four sequences were reinforced equally often. If the VI schedule arranged a reinforcement, and if the reinforcement-selection mechanism assigned that reinforcement to the sequence BA, then a bird would be rewarded for pecking the key once, waiting 4 sec, pecking the key once, waiting 1.5 sec, and pecking the key once. The reinforcement remained available until this sequence was emitted and the reinforcement was collected. Reinforcement could not be arranged for another sequence until this one occurred and was reinforced.

A sequence containing an IRT in neither class A nor class B could not be reinforced, except in condition U, in which reinforcements depended only on the terminal IRT.

Other procedural details. There was a blackout of 0.3 sec after every response to provide visual response feed-back. Reinforcement consisted of access to mixed grain for 1.75 sec. Each session lasted until a bird received its fiftieth reinforcement (the first five conditions) or until 1 hr elapsed (the last two conditions). Experimental conditions were terminated at times more dependent on convenient access to the computer than on a rational, or even arbitrary, criterion of behavioral stability.

Table 1 shows that the conditions lasted for about as many days as is standard practice in experiments on concurrent schedules of reinforcement. The replication of condition AB was, however, an exception and was continued for a longer time because apparatus problems altered two pigeons' eating behavior. Sessions were conducted seven days a week. The three subjects performed simultaneously but independently.

RESULTS

Two preliminary statements should be made before the major findings are presented. First, previous research has indicated that certain characteristics of responding on one-key *conc* VI VI schedules of reinforcement for two classes of IRTs depend on the overall density of reinforcement, but that the dependency is minimal if the total number of reinforcements per hour is at least 20 or 30 (Shimp, 1970). The overall reinforcement rate in the present experiment was maintained within a range of from 25 to 35 reinforcements per hour, with a few unimportant exceptions in either direction. The second preliminary statement concerns the shapes of the IRT distributions. It is sufficient to note that the IRT distributions were clearly bimodal, having two non-overlapping sub-distributions corresponding to the two classes of shorter and longer reinforced IRTs. These distributions of IRTs, and also

the percentages of IRTs falling within the intervals of reinforced IRTs, were similar to those described previously for *conc VI VI* schedules for two IRTs (Shimp, 1968, 1969b, 1970). Therefore, it is reasonable in the present paper to refer to two distinct classes of operants, namely, IRTs within classes A and B.

Sequential Statistics

Relative frequencies of sequences. The relative frequency of one of the four possible sequences of two successive IRTs was computed by dividing the frequency of occurrence of that sequence by the sum of the frequencies of occurrence of all four sequences. Only sequences consisting of two consecutive IRTs both belonging to classes A or B were included. For instance, if a bird terminated an IRT in, for example, class A, then one in neither class A nor class B, and then one in class B, the resulting sequence was not an instance of sequence AB.

Table 2 shows the individual relative frequencies and Table 3 shows the group means.

In Table 3, the data are averaged also over conditions with the same reinforcement parameters. Tables 2 and 3 show that the sequence AA occurred relatively infrequently in condition B, and relatively often in conditions A and U. The sequence BB occurred relatively infrequently in condition U, occurred more often in condition A, and most often in conditions AB and B. The sequences AB and BA tended to occur most often in condition B. Note that the sequences AB and BA occurred approximately equally often in every condition. This near equality undoubtedly was an artifact. The sequences AB and BA define "switches" from A to B and from B to A, respectively, and the number of switches in one direction had to equal the number of switches in the other direction (except for small differences attributable to the occasional IRTs in neither class A nor class B).

When all four sequences were reinforced equally often (condition AB), the shortest sequence, AA, occurred most often, AB and BA less often, and the longest sequence, BB, occurred least often.

Table 2
Sequential Statistics¹

Order of Conditions	Subject	Relative Frequencies of Sequences				Conditional Relative Frequencies		Overall Relative Frequency of Class A
		P(AA)	P(AB)	P(BA)	P(BB)	P(A A)	P(A B)	P(A)
AB	1	0.422	0.232	0.226	0.120	0.644	0.667	0.600
	2	0.301	0.284	0.308	0.088	0.508	0.779	0.621
	3	0.332	0.264	0.312	0.093	0.512	0.746	0.624
B	1	0.178	0.403	0.345	0.075	0.339	0.845	0.421
	2	0.184	0.336	0.381	0.099	0.326	0.773	0.554
	3	0.200	0.360	0.398	0.042	0.333	0.896	0.547
A	1	0.558	0.214	0.199	0.030	0.737	0.879	0.736
	2	0.426	0.268	0.231	0.075	0.648	0.784	0.696
	3	0.546	0.216	0.207	0.031	0.724	0.882	0.773
AB	1	0.322	0.319	0.304	0.056	0.510	0.857	0.566
	2	0.322	0.284	0.293	0.102	0.523	0.738	0.600
	3	0.462	0.247	0.272	0.020	0.629	0.926	0.738
U	1	0.564	0.187	0.239	0.010	0.696	0.948	0.757
	2	0.373	0.280	0.323	0.023	0.535	0.925	0.668
	3	0.498	0.242	0.239	0.021	0.671	0.918	0.741
B	1	0.179	0.357	0.337	0.128	0.340	0.742	0.512
	2	0.166	0.365	0.375	0.094	0.306	0.796	0.530
	3	0.238	0.346	0.396	0.019	0.374	0.948	0.530
U	1	0.474	0.248	0.260	0.018	0.643	0.939	0.769
	2	0.243	0.307	0.366	0.084	0.396	0.790	0.609
	3	0.556	0.246	0.195	0.004	0.740	0.986	0.785

¹Entries are means over the last three days of a condition.

Table 3

Sequential Statistics

(Averaged over three subjects and over conditions with the same reinforcement parameters.)

Condition	Relative Frequencies of Sequences				Conditional Relative Frequencies		Overall Relative Frequency of Class A
	P(AA)	P(AB)	P(BA)	P(BB)	P(A A)	P(A B)	P(A)
AB	0.360	0.272	0.286	0.080	0.554	0.786	0.624
B	0.191	0.361	0.372	0.076	0.336	0.833	0.516
A	0.510	0.233	0.212	0.045	0.703	0.848	0.735
U	0.451	0.252	0.270	0.027	0.614	0.918	0.722

The relative frequencies of the sequences show that, in general, a sequence occurred more frequently when it was reinforced more frequently. In addition, when all sequences were reinforced equally often, a shorter sequence tended to occur more often than a longer one.

Conditional relative frequencies of an IRT in class A. Tables 2 and 3 also show the relative frequency of an IRT in class A, conditional on the duration of the preceding IRT. These conditional relative frequencies are computed from the relative frequencies of the four sequences. The conditional relative frequency of an IRT in class A, given that the preceding IRT also was in class A, equals the relative frequency of the sequence AA divided by the sum of the relative frequencies of the sequences AA and AB. Similarly, the conditional relative frequency of an IRT in class A, given that the preceding IRT was in class B, equals the relative frequency of BA divided by the sum of the relative frequencies of BA and of BB. The stochastic independence, or dependence, of successive IRTs is inferred from these conditional relative frequencies. That is, if the conditional probability of an IRT in class A, given that the preceding IRT was in class A, equals the conditional probability of an IRT in class A, given that the preceding IRT was in class B, then, clearly, the probability of an IRT does not depend on the duration of the preceding IRT, and successive IRTs are said to be independent (Feller, 1957). Otherwise, the probability of an IRT in class A is not constant, and successive IRTs are said to be dependent. Tables 2 and 3 show that the two conditional relative frequencies were not even approximately equal in any condition. Indeed, in condition B they differed by as

much as 0.5. Specifically, the relative frequency of an IRT in class A was more than twice as great after a B than after an A. It would appear that successive IRTs were not independent: the duration of an IRT depended heavily on the preceding IRT.

Relative Frequencies of Interresponse Times in Class A.

The last columns of Tables 2 and 3 show the relative frequency of IRTs in class A. This relative frequency was calculated by dividing the number of IRTs in class A by the number of IRTs in classes A and B.

The schedule of reinforcement in condition U was an unmodified *conc VI VI* for two classes of IRTs. Therefore, one would expect the relative frequency of A approximately to equal the relative reciprocal of the length of class A (Shimp, 1969b). Here, the relative reciprocal of the length of class A was $(1/1)/[(1/1) + (1/3)]$, which equals 0.75. Tables 2 and 3 show that the relative frequency of A was quite near to 0.75 for Birds 1 and 3, but for Bird 2, it was slightly too low.

Averaged over both conditions U, slightly fewer than half of the reinforcements were collected by responses terminating an IRT in class A: the actual proportions were 0.458, 0.409, 0.461, for Birds 1, 2, and 3, respectively. The low value for Bird 2 may partly explain why the relative frequency of IRTs in class A for Bird 2 was somewhat below the value predicted from the relative reciprocal of the length of class A.

In condition B, the IRT preceding reinforced IRTs always belonged to class B. This arrangement reduced the relative frequency of IRTs in class A by approximately 0.2 below the matching value, despite the fact that class

A continued to receive approximately half of the reinforcements. In condition AB, only half of the IRTs preceding reinforced IRTs belonged to class B, with the result that the relative frequency of IRTs in class A was just slightly less than the matching value. In condition A, the IRT preceding reinforced IRTs always belonged to class A, and the relative frequency of IRTs in class A was approximately equal to the relative reciprocal of the length of class A. These data demonstrate that the relative frequency of IRTs in class A depended on the IRT preceding reinforced IRTs.

DISCUSSION

The present experiment was designed to investigate further the way in which control may be obtained over the function relating response probability to the time since the last response. It was designed specifically to see if the duration of the IRT preceding reinforced IRTs affects this function. The results clearly show that it does. The proportion of cases in which the IRT preceding the reinforced IRT belonged to class A was varied, and as it increased, so did the frequency of occurrence of IRTs in class A. In the particular case in which all the IRTs preceding reinforced IRTs belonged to class A, the relative frequency of IRTs in class A approximately equalled the relative reciprocal of the length of class A, as it does in ordinary *conc VI VI* for two IRTs (Shimp, 1969b).

The matching-to-relative-reciprocal relation-ship has been taken to mean that the probability of a response, t sec after the last response, equals the relative reciprocal of t . The present results show more precisely how this equality ought to be interpreted. There in fact is not a probability of a response t sec after the last response. There are two different probabilities, depending on whether the previous IRT was in class A or class B. Tables 2 and 3 show that the probability of a response 1.0 sec after the last response was higher than the relative reciprocal of 1.0 if the preceding IRT was in class B, but it was lower than the relative reciprocal if the preceding IRT was in class A. (Recall that the relative reciprocal of 1.0 was 0.75 in the present experiment.) The matching-to-relative-reciprocal relation describes an average response probability that does not

seem to be representative of any actual momentary response probabilities.

This fact about the proper interpretation of the matching-to-relative-reciprocal relation is but a special case of the general finding. The probability of a response as a function of the time since the last response may not be portrayed accurately by any transformation of the IRT frequency distribution. Specifically, neither the relative-frequency distribution nor the IRTs/Op may accurately estimate the response probability. Each of these distributions will be an average of several conditional distributions whenever sequential dependencies are present. The conditional distributions then provide more accurate estimates of actual response probabilities than does their average (see also Williams, 1968).

Catania (1971) conducted a two-key experiment designed to investigate the effects of the response preceding a reinforced one. He speculated that the response preceding a reinforced one contributed to subsequent response probability to an extent depending on the time separating it from reinforcement: reinforcement was presumed to increase the strength not only of the response for which it was delivered, but also the strength of any preceding responses, according to a delay-of-reinforcement gradient (also see Dews, 1969). Accordingly, the relative frequency of IRTs in class A in the present experiment should have been, and indeed was, highest when the shortest sequence was most often reinforced, as in condition A, intermediate in condition AB, and lowest when the longest sequence was most often reinforced as in condition B. In condition AB, where all four sequences were reinforced equally often, their relative frequencies of occurrence were also as they should have been according to this view, with the shortest sequence AA, most frequent, AB and BA intermediate, and the longest sequence BB, least frequent.

An account for the present data such as the above one is not the only possible one in terms of delay-of-reinforcement. According to one of several possible alternative views, a subject in the present experiment learned to choose, immediately after terminating one IRT, how long to wait before the next response. Accordingly, the chosen waiting time, or IRT, intervened between a choice and subsequent reinforcement. Thus, an IRT was itself a delay

of reinforcement (Staddon, 1968; Shimp, 1969a, b). This viewpoint obviously predicts the same rank orderings for the present data as does Catania's. It is representative of the widespread neglect of sequential phenomena in general that neither viewpoint even addresses, let alone accounts for, the sequential dependencies that were obtained to such a marked extent in the present experiment.

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