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THE LAW OF EFFECT AND AVOIDANCE: A QUANTITATIVE RELATIONSHIP BETWEEN RESPONSE RATE AND SHOCK-FREQUENCY REDUCTION[1]

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Two experiments were conducted to investigate the quantitative relationship between response rate and reinforcement frequency in single and multiple variable-interval avoidance schedules. Responses cancelled delivery of shocks that were scheduled by variable-interval schedules. When shock-frequency reduction was taken as the measure of reinforcement, the relationship between response rate and reinforcement frequency on single variable-interval avoidance schedules was accurately described by Herrnstein's (1970) equation for responding on single variable-interval schedules of positive reinforcement. On multiple variable-interval avoidance schedules with brief components, asymptotic relative response rate matched relative shock-frequency reduction. The results suggest that many interactions between response rates and shock-frequency reduction in avoidance can be understood within the framework of the generalized matching relation, as applied by Herrnstein (1970) to positive reinforcement.

Herrnstein (1970) demonstrated that many of the interactions between positive reinforcement and response rates can be understood in terms of a set of equations generalized from the matching relationship observed in concurrent variable-interval (VI) schedules. The matching equation specifies that

$$\frac{R_1}{R_1 + R_2} = \frac{r_1}{r_1 + r_2} \qquad (1)$$

where R_1 and R_2 are response frequencies for two alternatives, and r_1 and r_2 are the rates of reinforcement provided by those two alternatives, *i.e.,* relative response rate matches obtained relative reinforcement frequency (Herrnstein, 1961).

Herrnstein (1970) pointed out that at every moment, a set of alternative responses confronts the animal, and each action is therefore the outcome of a choice. Thus, even on single-response procedures the animal is in a concurrent situation, although the experimenter is monitoring only one of the alternative responses and reinforcers. Response rate on a single schedule can then be considered to be a function of the frequency of reinforcement for that response relative to all the other sources of reinforcement for competing responses. Herrnstein therefore suggested that the equation

$$R_1 = \frac{kr_1}{r_1 + r_0} \qquad (2)$$

may be appropriate for describing response rate-reinforcement rate interactions in single-response situations. In this equation, the parameter k represents the asymptotic response rate when there is no reinforcement for competing responses, while r_0 represents the total reinforcement for other responses in the experimental situation. He showed that this equation provided an excellent fit to the data obtained by Catania and Reynolds (1968) for six pigeons responding on VI schedules with rates of food reinforcement ranging from 10 to 300 per hour.

de Villiers (1972) presented evidence that Herrnstein's quantitative analysis of response rate-reinforcement rate interactions can be extended to negative reinforcement (*i.e.,* the termination or avoidance of aversive stimulation), with shock-frequency reduction as the

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[1]This paper is dedicated to Mrs. Antoinette Papp in the year of her retirement. Without her dedicated work, much of the research on the experimental analysis of behavior carried out at Harvard University between 1955 and 1972 would not have been done. Thanks are also due to Mrs. V. Upham for her help in running the experiments, and to Professor R. J. Herrnstein for his advice during this research. This research was supported by a grant from the National Institute of Mental Health to Harvard University. Reprints may be obtained from the author, Psychology Department, William James Hall, 33 Kirkland Street, Cambridge, Mass. 02138.

reinforcer controlling avoidance (Herrnstein and Hineline, 1966; Herrnstein, 1969). de Villiers pointed out that the common avoidance schedules used in free-operant research [(*e.g.*, the standard Sidman schedule (1953) or Sidman's adjusting schedule (1962)] are inappropriate for determining the quantitative relations between response rate and negative reinforcement variables. On these schedules, response rate is largely determined by regularities in the temporal relations between shocks and responses and is not free to vary widely with changes in rate of reinforcement for avoidance. de Villiers therefore used random-interval (RI) avoidance schedules in which responses cancelled the delivery of shocks scheduled at different random intervals. On this schedule, both received shock rate and shock-frequency reduction (scheduled shock rate minus received shock rate) can be measured, and response rate is not constrained by any fixed temporal relations between responses and shocks.

de Villiers found that when shock-frequency reduction was substituted for rate of positive reinforcement, long-term behavioral contrast in multiple RI avoidance schedules could be accounted for by Herrnstein's (1970) equation for response rate-reinforcement interaction in multiple schedules,

$$R_1 = \frac{kr_1}{r_1 + mr_2 + r_0} \qquad (3)$$

k and r_0 are the parameters defined earlier for Equation 2, and m is a parameter varying between 0 and 1.0 that indicates the degree of interaction between the reinforcement conditions of the two components of the multiple schedule.

The present two experiments set out to test further the extension of Herrnstein's equations to avoidance by examining the quantitative relationship between response rate and both shock-frequency reduction and received shock rate on single VI avoidance schedules (Experiment I), and on multiple VI avoidance schedules with brief component duration (Experiment II).

The matching equation (1) has been found to apply not only to responding on concurrent VI schedules of positive reinforcement, but also to responding on multiple VI schedules with very brief components. Shimp and Wheatley (1971) and Todorov (1972) have shown that relative response rates on multiple VI schedules reach an asymptote near that predicted by the matching equation when component duration is systematically shortened. This finding can be accounted for by Equation 3, Herrnstein's equation for multiple schedules. As the interaction between the components increases with shorter component duration, the interactive parameter m approaches its maximum value of 1.0. The equation is then the same as that governing absolute response rates in concurrent schedules, in which interaction between the two schedules is maximal, *i.e.*,

$$R_1 = \frac{kr_1}{r_1 + r_2 + r_0} \qquad (4).$$

The matching equation would then hold between relative response rate and relative reinforcement rate.

$$\frac{R_1}{R_1 + R_2} = \frac{\dfrac{kr_1}{r_1 + r_2 + r_0}}{\dfrac{kr_1}{r_1 + r_2 + r_0} + \dfrac{kr_2}{r_2 + r_1 + r_0}} = \frac{r_1}{r_1 + r_2} \qquad (5).$$

This formal similarity in reinforcement interactions between concurrent schedules and multiple schedules with brief components has been investigated by Killeen (1972). He arranged component alternation for a pigeon responding on multiple VI schedules according to the changeover rate of another pigeon responding on concurrent VI schedules in a second chamber. Killeen found that when component durations in the multiple schedule are set at values that approximate those that the pigeon would choose on concurrent schedules, relative response rate matches relative reinforcement rate on multiple schedules as it does on concurrent schedules.

It has proved difficult to study concurrent avoidance schedules because shocks occur some time after responses on these schedules. There is therefore no clear correlation between a received shock and the lever associated with the schedule that arranged that shock. While responding on one of the levers, the animal can receive a shock scheduled by either of the two schedules. Many animals therefore fail to alternate between the two levers in a concurrent avoidance situation and confine their responses almost exclusively to one lever, because that reduces the shock frequency enough to maintain responding (Sidman, 1966). However, if multiple schedules with very brief components produce the same quantitative relationship between response rate and reinforcement rate as a concurrent schedule, it should be possible to use multiple VI avoidance schedules to investigate how the matching relation might apply to avoidance. With such schedules, received shock rates and shock-frequency reduction are clearly associated with each component of the schedule. As component duration is shortened, relative response rate should increase until it reaches some maximum value, as in the Shimp and Wheatley (1971) and Todorov (1972) experiments. Experiment II therefore sought to investigate whether at this asymptotic value, relative response rate on multiple VI avoidance schedules would show some simple matching relation to either relative received shock rate or relative shock-frequency reduction.

METHOD

Subjects

Seven male Lashley-strain rats, approximately five months old at the beginning of the experiments, served. Four rats were used in Experiment I (R8, R13, R2, and R3) and three in Experiment II (R7, R9, and R11). R2 and R3 had previous experience on a VI 15-sec avoidance schedule in a different experimental chamber but the other rats were experimentally naive. All rats had free access to food and water in their home cages.

Apparatus

The experimental chambers were standard rat boxes 23 cm long, 21 cm wide, and 20 cm high, with metal ends, Plexiglas sides and ceiling, and were illuminated by a red houselight. In both boxes the bars constituting the floor grids were 6.3 mm in diameter and placed 2.54 cm apart center-to-center. The levers and metal ends of the chambers, as well as the floor grids, were wired into the shock circuits. Alternating current shocks from constant current sources passed through scrambling devices to the floor, levers, and metal walls of each box. In the box used for Experiment I, a single response lever was mounted in the middle of the front panel 6.5 cm above the grid floor. In the box used for Experiment II, two levers were mounted on the front panel 9 cm apart and 6.5 cm above the grid floor. A white stimulus light was situated 3 cm above each lever in this second box. In both experiments, feedback for a response was provided by a click from a feedback relay.

For both experiments, conventional electromechanical circuitry controlled the stimulus events and recorded the data on counters. Supplementary data were recorded on Gerbrands cumulative recorders.

EXPERIMENT I—SINGLE VI AVOIDANCE SCHEDULES

Procedure

Throughout the experiment, sessions lasted for 90 min, with data being collected from the whole session. Shocks of 1.5-mA force and 0.3-sec duration, were scheduled at variable intervals by VI tapes using VI progressions after Fleshler and Hoffman (1962). If no lever-press response was made, all scheduled shocks were presented. The first response made after a scheduled shock, whether or not that shock had been presented, prevented the presentation of only the next scheduled shock. Extra responses between two scheduled shocks did not avoid further shocks. All scheduled shocks could therefore be avoided if the rat responded within every inter-shock interval. This VI avoidance schedule shares all of the advantages of the random-interval schedules used by de Villiers (1972), *i.e.,* no fixed temporal relations between responses and shocks, and the probability of a shock being scheduled after one has been presented is constant over time.

The four rats were initially studied for ten 90-min sessions on a VI 15-sec avoidance schedule. All rats showed rapid acquisition of the avoidance response, and after two or three sessions were responding steadily at rates in excess of 15 responses per minute. Thereafter, they were studied in the sequence of conditions outlined in Table 1. An experimental condition was changed when the response rate, plotted against sessions, looked stable for the last five or six sessions. This required from 15 to 20 sessions.

Results

Figure 1 shows cumulative records from three of the rats on five different VI avoid-

Table 1

Response rate, received shock rate, and shock-frequency reduction averaged over the last five sessions in each condition for each rat. The five-session ranges are shown in parentheses.

Schedule	*Response Rate (per min)*	*Received Shock Rate (per min)*	*Shock-Frequency Reduction (per min)*	*Response Rate (per min)*	*Received Shock Rate (per min)*	*Shock-Frequency Reduction (per min)*
		R 8			*R 13*	
VI 15-sec	17.4	1.47	2.60	42.0	0.52	3.58
	(16.0-18.4)	(1.34-1.60)	(2.48-2.65)	(39.9-42.8)	(0.41-0.64)	(3.55-3.66)
VI 30-sec	10.6	0.88	1.15	31.6	0.24	1.78
	(9.8-10.9)	(0.85-0.92)	(1.10-1.20)	(29.3-33.9)	(0.18-0.30)	(1.73-1.84)
VI 45-sec	6.8	0.56	0.78	28.4	0.10	1.24
	(6.3-7.8)	(0.53-0.59)	(0.74-0.82)	(26.4-29.1)	(0.07-0.13)	(1.22-1.26)
VI 60-sec	4.7	0.41	0.58	22.0	0.05	0.96
	(4.2-5.4)	(0.37-0.47)	(0.51-0.64)	(19.0-25.5)	(0.02-0.07)	(0.92-0.99)
VI 75-sec				20.8	0.04	0.80
				(19.3-21.9)	(0.02-0.04)	(0.78-0.82)
VI 60-sec				20.4	0.07	0.95
				(19.0-21.8)	(0.06-0.09)	(0.94-0.96)
VI 45-sec	6.1	0.54	0.78	21.7	0.14	1.23
	(5.2-7.0)	(0.49-0.58)	(0.75-0.83)	(19.0-23.6)	(0.11-0.16)	(1.20-1.25)
VI 30-sec	6.5	0.94	1.09	23.2	0.22	1.83
	(5.7-7.1)	(0.90-1.04)	(1.00-1.16)	(20.7-25.9)	(0.17-0.25)	(1.79-1.90)
VI 15-sec	15.2	1.61	2.39	31.3	0.58	3.48
	(13.9-16.6)	(1.59-1.64)	(2.20-2.50)	(29.8-32.6)	(0.55-0.63)	(3.34-3.58)
		R 2			*R 3*	
VI 60-sec	20.3	0.06	0.95	10.4	0.14	0.85
	(17.9-25.6)	(0.02-0.08)	(0.91-0.99)	(9.2-11.9)	(0.13-0.15)	(0.77-0.88)
VI 45-sec	25.5	0.07	1.27	11.9	0.18	1.17
	(22.7-27.5)	(0.05-0.08)	(1.25-1.29)	(10.9-13.1)	(0.16-0.21)	(1.14-1.20)
VI 30-sec	31.7	0.14	1.91	15.3	0.33	1.69
	(29.4-34.0)	(0.11-0.16)	(1.90-1.93)	(14.4-16.8)	(0.30-0.37)	(1.67-1.71)
VI 15-sec	35.6	0.45	3.57	16.9	0.95	3.08
	(32.5-38.9)	(0.30-0.57)	(3.43-3.69)	(15.6-18.0)	(0.88-1.08)	(2.97-3.19)
VI 22.5-sec	32.8	0.26	2.27	15.2	0.63	2.02
	(30.0-35.8)	(0.19-0.35)	(2.20-2.35)	(14.0-16.3)	(0.52-0.73)	(1.86-2.17)
VI 30-sec	28.5	0.15	1.87	13.3	0.47	1.58
	(26.4-31.7)	(0.11-0.21)	(1.76-1.95)	(12.3-14.2)	(0.39-0.52)	(1.50-1.66)
VI 45-sec	24.7	0.11	1.27	10.8	0.23	1.14
	(22.9-26.6)	(0.08-0.15)	(1.22-1.30)	(9.8-12.3)	(0.19-0.26)	(1.10-1.17)
VI 60-sec	20.5	0.10	0.94	8.9	0.15	0.89
	(19.4-22.9)	(0.07-0.12)	(0.91-0.99)	(8.5-9.4)	(0.13-0.17)	(0.86-0.91)

ance schedules. The records from the fourth rat were comparable to these, although response rates were lower and received shock rates substantially higher. Although on this VI avoidance procedure, one response between two scheduled shocks is sufficient to reduce the shock rate by 50%, all rats emitted responses at a high and steady rate, much like the performance generated by VI schedules of food reinforcement. Though brief bursts of short interresponse times occurred immediately after a shock was presented, it is clear from the records in Figure 1 that these post-shock response bursts account for little of the responding. On the longer VI schedules, two animals received as few as five or six shocks in the entire 90-min session, yet produced steady response rates between 15 and 20 responses per minute.

On the shorter VI avoidance schedules, received shock rate, and therefore shock-frequency reduction (scheduled shock rate minus received shock rate), is somewhat dependent on response rate. The faster the animal responds, the lower the shock rate and the higher the shock-frequency reduction. How-

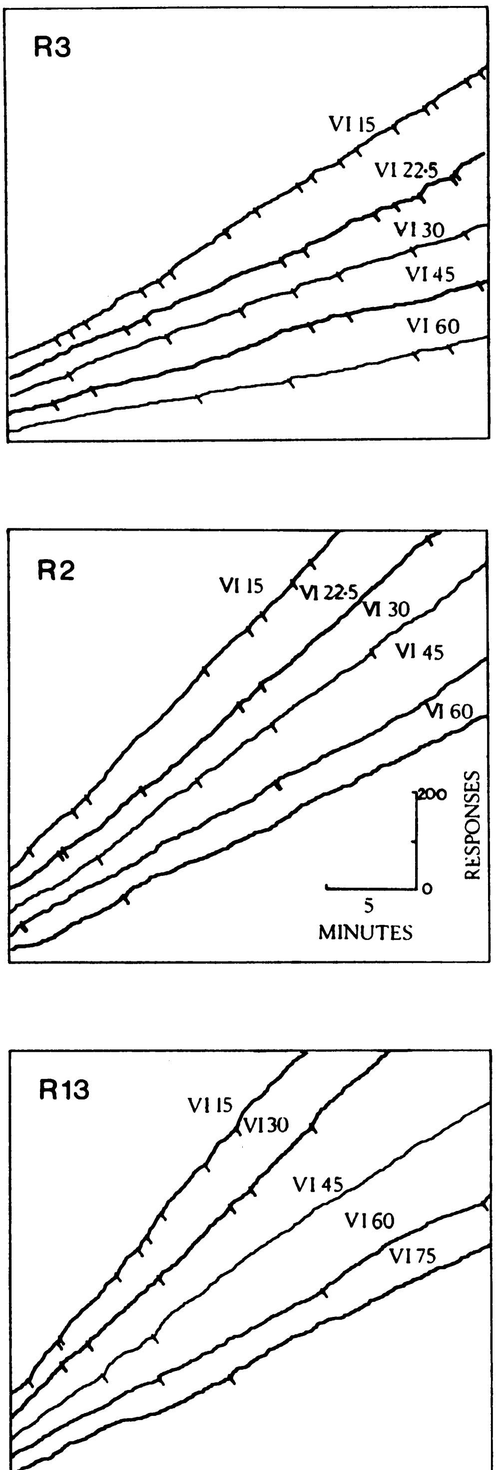

Fig. 1. Cumulative records from three rats responding on five different VI avoidance schedules. The presentation of a shock to the animal is marked by a downward deflection of the pen.

ever, even on the shortest VI schedules, a response rate in the region of 25 responses per minute can vary by as much as five responses per minute without any appreciable change in received shock rate, since the shocks are mostly received from the short inter-shock intervals. Furthermore, for VI schedules of food reinforcement within this range (15 sec to 45 sec), rate of food reinforcement also covaries with response rate to a considerable degree. For the longer VI avoidance schedules (> 45 sec), shock rate is far less dependent on changes in response rate.

For each rat, the mean response rate, received shock rate, and shock-frequency reduction (scheduled shock rate minus received shock rate) were calculated for the last five sessions at each VI value. Table 1 shows these means together with the range of values over the five sessions for each VI schedule. Received shock rate and shock-frequency reduction do not always sum exactly to the stated VI value (*e.g.*, 4.0 shocks per minute on a VI 15-sec), since especially on short VI schedules, the shock rate actually scheduled by the VI tape varies slightly from session to session.

If Equation 2 accurately describes the relationship between response rate and reinforcement rate on single VI schedules, a linear relationship should hold between the reciprocal of response rate and the reciprocal of reinforcement rate.

$$R_1 = \frac{kr_1}{r_1 + r_0} \qquad (2)$$

$$\frac{1}{R_1} = \frac{r_1 + r_0}{kr_1}$$

$$= \frac{1}{k} + \left(\frac{r_0}{k}\right)\frac{1}{r_1} \qquad (6).$$

In Figure 2, the reciprocal of response rate is plotted against the reciprocal of shock-frequency reduction (in shocks avoided per minute) for each rat. The open circles show the mean of the last five sessions at each VI value, and where there are two determinations of the values for a given VI schedule, the mean of those two determinations is shown by the open triangles. A sizeable hysteresis effect was found for R8 and R13, but this effect was somewhat smaller for R3 and negligible for R2.

Equation 6 was fitted to the data for each rat by the method of least squares and the ob-

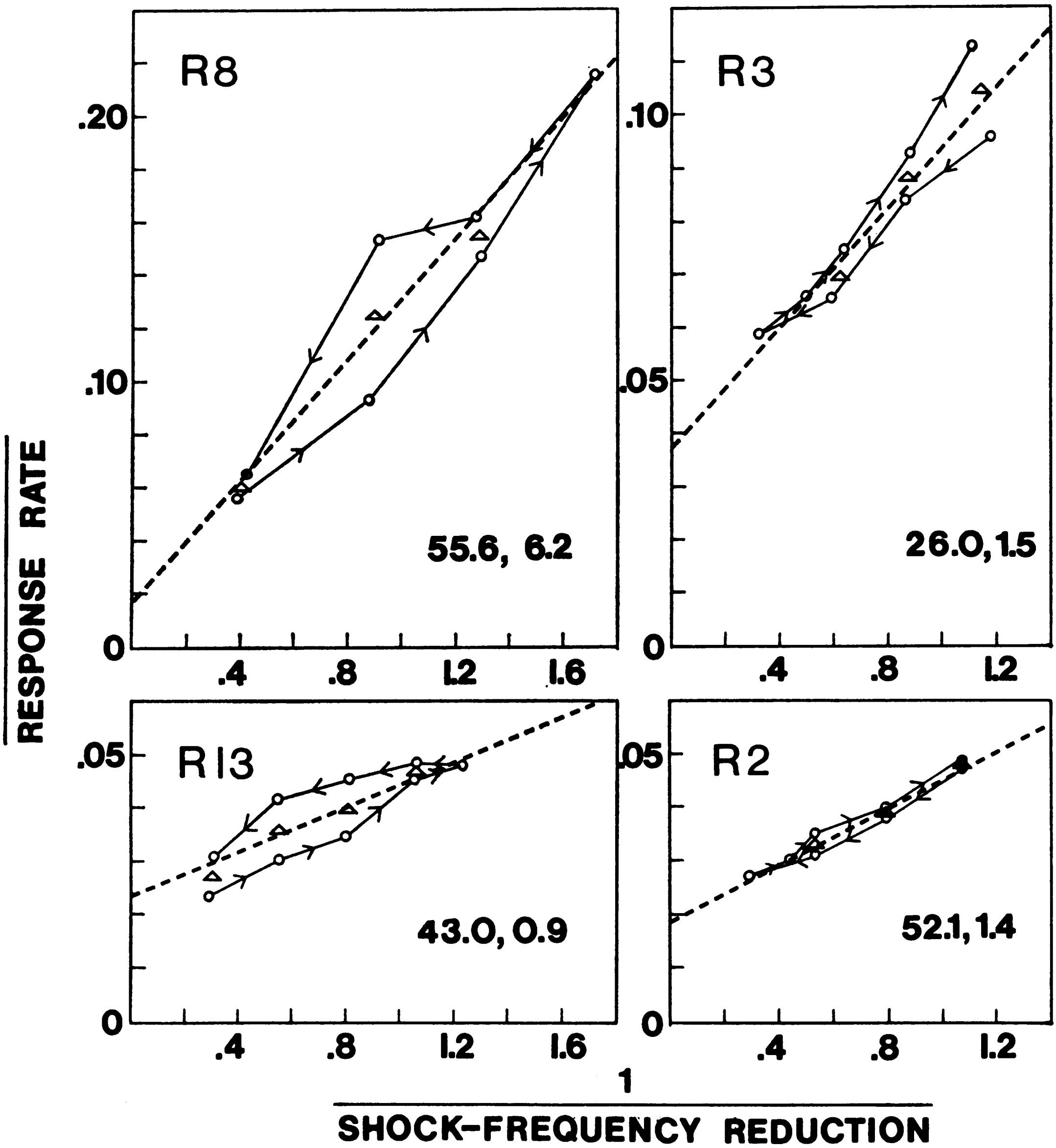

Fig. 2. The reciprocal of response rate plotted against the reciprocal of shock-frequency reduction on the different VI schedules for each rat. The open circles represent the mean of the last five sessions at each VI value. The open triangles show the mean of the two determinations for a given VI schedule. The broken lines represent the least-squares fit of Equation 6 for each rat. The first number in the lower right-hand corner of each panel is k in responses per minute and the second is r_0 in shocks avoided per minute.

tained functions are plotted in Figure 2 by the broken lines. In fitting this function, if there were two determinations of the values for a given VI schedule, the mean of those determinations was used. The k and r_0 values that were calculated from these functions for each rat are shown in the right-hand corner of each panel of the figure, the k value on the left and the r_0 value on the right. The k value is given in responses per minute and r_0 in shocks avoided per minute. These values are of the same order of magnitude as those found by de Villiers (1972) for the five rats in his previous experiment. Equation 6, with the parameter values shown in the figure, accounts for over 95% of the data variance for all four of the rats: 99.2% for R8, 99.3% for R13, 98.6% for R3, and 97.8% for R2. This result compares favorably with the fit of this equation to the data from Catania and Reynolds (1968) for pigeons responding on VI schedules of food reinforcement.

For R8 and R3, using received shock rate in place of shock-frequency reduction as the variable controlling avoidance produced roughly as good a fit to Equation 6. For R13 and R2, however, the function relating the reciprocal of response rate and the reciprocal of received shock rate was not as clearly linear. For these two rats, the least-squares fit of Equation 6 to the data accounted for 78.6% and 86.3% of the variance respectively, still a sizeable proportion, but somewhat less than that obtained with shock-frequency reduction. Furthermore, for R13 the value derived for k was lower than the mean response rate obtained on the VI 15-sec schedule, implying that r_0 was negative in value while this schedule was in effect, an unlikely, if not impossible, result.

EXPERIMENT II—MATCHING IN MULTIPLE VI AVOIDANCE SCHEDULES

Procedure

Throughout the experiment, sessions were 2 hr in duration, with data being taken from the entire session. Shocks of 1.5-mA force and 0.3-sec duration were scheduled at variable intervals by VI tapes using VI progressions after Fleshler and Hoffman (1962). The same avoidance contingency was in effect as in Experiment I.

Table 2

Mean response rates, received shock rates, and shock-frequency reduction over the last six sessions in each condition for each rat.

Right	Left	Component Duration	Response Rate (per min) Right	Response Rate (per min) Left	Received Shock Rate (per min) Right	Received Shock Rate (per min) Left	Shock-Frequency Reduction (shocks avoided per min) Right	Shock-Frequency Reduction (shocks avoided per min) Left
R 7								
mult VI 15-sec	VI 15-sec	15-min	17.0	20.6	0.49	0.39	3.54	3.55
mult VI 20-sec	VI 40-sec	6-min	15.5	12.2	0.49	0.29	2.52	1.26
		2-min	12.5	7.6	0.65	0.32	2.42	1.21
		40-sec	12.2	4.9	0.66	0.39	2.41	1.19
		13.3-sec	13.6	5.6	0.69	0.39	2.46	1.16
		40-sec	12.9	5.9	0.72	0.39	2.39	1.20
mult VI 40-sec	VI 20-sec	6-min	9.1	12.1	0.32	0.50	1.20	2.43
		40-sec	6.1	11.7	0.30	0.47	1.26	2.58
mult VI 45-sec	VI 15-sec	40-sec	8.2	20.8	0.19	0.34	1.22	3.79
		13.3-sec	7.7	15.7	0.20	0.39	1.19	3.65
R 9								
mult VI 15-sec	VI 15-sec	15-min	14.6	16.4	0.74	0.59	3.31	3.37
mult VI 20-sec	VI 40-sec	6-min	10.8	6.8	0.70	0.40	2.23	1.15
		2-min	10.3	5.7	0.84	0.41	2.24	1.13
		40-sec	12.0	6.1	0.54	0.33	2.52	1.26
		13.3-sec	13.2	7.5	0.46	0.27	2.51	1.23
		40-sec	13.4	7.3	0.52	0.27	2.51	1.30
mult VI 40-sec	VI 20-sec	6-min	8.1	12.1	0.34	0.67	1.20	2.31
		40-sec	3.5	7.5	0.42	0.70	1.19	2.31
mult VI 45-sec	VI 15-sec	40-sec	3.3	9.8	0.29	0.85	1.15	3.24
R 11								
mult VI 15-sec	VI 15-sec	15-min	33.5	32.2	0.45	0.47	3.61	3.54
mult VI 40-sec	VI 20-sec	40-sec	11.3	19.3	0.37	0.62	1.23	2.43
		2-min	9.7	14.4	0.34	0.84	1.20	2.25
		6-min	10.0	15.2	0.38	0.74	1.17	2.31
mult VI 45-sec	VI 15-sec	40-sec	10.1	32.9	0.20	0.48	1.20	3.64
		13.3-sec	11.9	30.6	0.22	0.50	1.17	3.56

During initial training, a single VI 15-sec schedule arranged shocks. Response on either of the two levers cancelled delivery of the shocks. By the end of the first 2-hr session, all three rats were responding steadily on both levers. The rats were then studied for ten 2-hr sessions during which only one or the other lever was present in the box and a VI 15-sec avoidance schedule was in force. The left- and right-hand levers were present in alternate sessions, and the stimulus light above the lever in operation was illuminated during the entire session.

The three rats were then studied in the multiple variable-interval variable-interval (*mult* VI VI) procedures outlined in Table 2, with both levers present. The two-component schedules of the multiple schedule were associated with different levers and were signalled by the illumination of the stimulus light above the lever in operation. The number of sessions conducted in each condition ranged from 15 to 21 for each bird.

Results

The VI avoidance schedules again generated steady response rates similar to those obtained in Experiment I. The mean response rates, received shock rates, and shock-frequency reduction (scheduled shock rate minus received shock rate) were calculated for each component of the multiple schedule from the last six sessions of each experimental condition. These data are summarized in Table 2.

Mean relative response rates, *i.e.*, response rate in the first component divided by the sum of the response rates in both components, and mean relative shock-frequency reduction, *i.e.*, shock-frequency reduction in the first component divided by the total shock-frequency re-

Table 3

Mean relative response rate, relative received shock rate, and relative shock-frequency reduction in the first component of the multiple schedule and the range over the last six sessions of each condition.

Schedule Right Left	Duration Component	Relative Response Rate Mean	Relative Response Rate Range	Relative Shock-Frequency Reduction Mean	Relative Shock-Frequency Reduction Range	Relative Received Shock Rate Mean	Relative Received Shock Rate Range
R 7							
mult VI 15-sec VI 15-sec	15-min	0.455	(0.411-0.507)	0.499	(0.496-0.509)	0.556	(0.455-0.610)
mult VI 20-sec VI 40-sec	6-min	0.558	(0.527-0.618)	0.667	(0.620-0.689)	0.633	(0.576-0.688)
	2-min	0.620	(0.582-0.661)	0.668	(0.649-0.680)	0.668	(0.625-0.753)
	40-sec	0.714	(0.703-0.738)	0.670	(0.655-0.696)	0.628	(0.580-0.682)
	13.3-sec	0.708	(0.676-0.729)	0.679	(0.659-0.684)	0.639	(0.588-0.694)
	40-sec	0.685	(0.654-0.718)	0.667	(0.647-0.686)	0.650	(0.609-0.725)
mult VI 40-sec VI 20-sec	6-min	0.428	(0.397-0.473)	0.331	(0.323-0.344)	0.388	(0.339-0.455)
	40-sec	0.343	(0.325-0.367)	0.328	(0.302-0.348)	0.391	(0.314-0.458)
mult VI 45-sec VI 15-sec	40-sec	0.282	(0.240-0.311)	0.244	(0.240-0.250)	0.367	(0.340-0.414)
	13.3-sec	0.329	(0.314-0.348)	0.246	(0.235-0.258)	0.339	(0.235-0.398)
R 9							
mult VI 15-sec VI 15-sec	15-min	0.472	(0.429-0.539)	0.496	(0.478-0.512)	0.557	(0.467-0.631)
mult VI 20-sec VI 40-sec	6-min	0.619	(0.531-0.695)	0.660	(0.634-0.686)	0.643	(0.557-0.705)
	2-min	0.644	(0.609-0.679)	0.666	(0.641-0.700)	0.667	(0.547-0.718)
	40-sec	0.664	(0.634-0.707)	0.667	(0.646-0.686)	0.617	(0.563-0.689)
	13.3-sec	0.639	(0.618-0.658)	0.671	(0.653-0.685)	0.629	(0.557-0.683)
	40-sec	0.649	(0.620-0.667)	0.658	(0.639-0.668)	0.660	(0.633-0.707)
mult VI 40-sec VI 20-sec	6-min	0.402	(0.383-0.426)	0.342	(0.332-0.357)	0.337	(0.265-0.386)
	40-sec	0.319	(0.306-0.335)	0.340	(0.333-0.346)	0.377	(0.315-0.435)
mult VI 45-sec VI 15-sec	40-sec	0.254	(0.215-0.304)	0.261	(0.225-0.278)	0.254	(0.189-0.356)
R 11							
mult VI 15-sec VI 15-sec	15-min	0.510	(0.495-0.521)	0.505	(0.496-0.512)	0.490	(0.444-0.548)
mult VI 40-sec VI 20-sec	40-sec	0.369	(0.324-0.394)	0.336	(0.331-0.347)	0.374	(0.300-0.466)
	2-min	0.402	(0.357-0.424)	0.348	(0.330-0.370)	0.292	(0.205-0.366)
	6-min	0.396	(0.370-0.427)	0.336	(0.325-0.347)	0.343	(0.292-0.385)
mult VI 45-sec VI 15-sec	40-sec	0.233	(0.184-0.270)	0.248	(0.236-0.258)	0.296	(0.212-0.266)
	13.3-sec	0.279	(0.254-0.320)	0.248	(0.238-0.265)	0.309	(0.232-0.351)

duction in both components, were calculated for the last six sessions of each experimental condition. Mean relative received shock rates, *i.e.,* shock rate in the first component divided by the overall shock rate in both components, were also calculated. These mean relative rates are given in Table 3 together with the range of values obtained over the last six sessions of each condition.

The mean relative response rate for each condition is plotted in Figure 3 for each of the rats. The horizontal solid lines show the mean relative shock-frequency reduction summed across different component durations. The relative shock-frequency reduction values given in Table 3 show that this line is an accurate reflection of the relative shock-frequency reduction at each component duration. Figure 3 and Table 3 show that as component duration was shortened for a given multiple VI avoidance schedule, relative response rate increased for the component with the greater shock-frequency reduction and decreased for the other component, until it reached asymptotic value for each component at 40-sec component duration. At this component duration, relative response rates for R7 and R9 approximately matched the relative shock-frequency reduction on the *mult* VI 20-sec VI 40-sec schedule. When the VI 20-sec schedule was shifted from the right to the left lever to counteract any position bias effects, matching was again obtained at 40-sec components for R7 and R9. For Rat R11, component duration was first set at 40-sec and then increased through 2-min to 6-min. For this rat, relative response rate in the component with the greater shock-frequency reduction was also higher at 40-sec

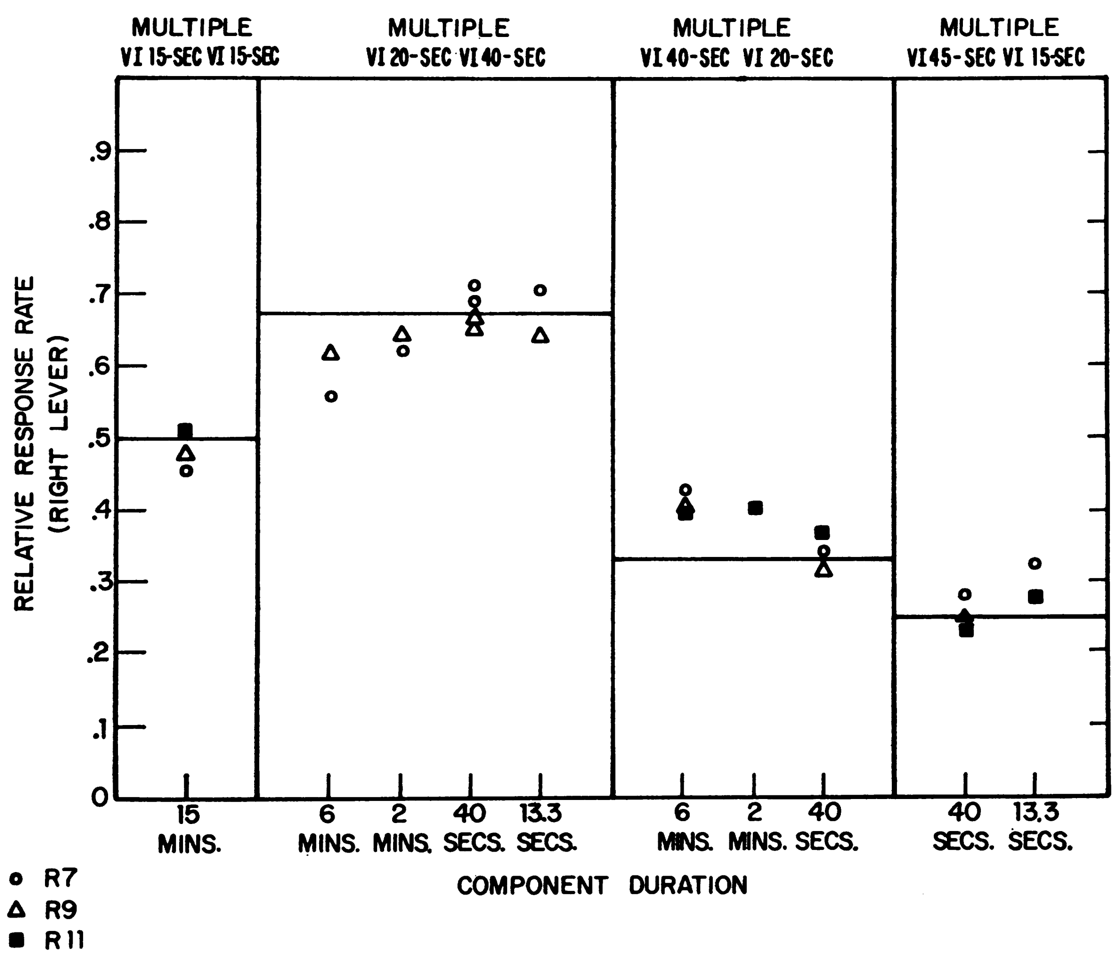

Fig. 3. Mean relative response rates for each rat for the last six sessions of each experimental condition. The mean relative shock-frequency reduction for each multiple schedule is shown by the horizontal solid lines.

components than at the longer components. Deviation from matching to the relative shock-frequency reduction was smallest at the 40-sec component duration. For all three rats, relative response rates also approximately matched relative shock-frequency reduction when the schedule was changed to a *mult* VI 45-sec VI 15-sec with 40-sec components.

In both the *mult* VI 20-sec VI 40-sec and the *mult* VI 45-sec VI 15-sec conditions, relative response rates for the component with greater shock-frequency reduction did not further increase when the component duration was shortened still further to 13.3 sec. In fact, relative response rates moved slightly in the direction of indifference (0.50) with the 13.3-sec components, especially in the *mult* VI 45-sec VI 15-sec condition. This suggests that the interaction between the two components was nearest to maximal (*i.e.*, m equals 1.0) when the components were 40 sec long. A similar effect was found for most of the pigeons in the Shimp and Wheatley (1971) and Todorov (1972) experiments with positive reinforcement when component duration was shortened beyond the value at which maximal relative response rate was obtained in the component with the greater relative reinforcement frequency.

Since the maximal relative response rates were obtained at 40-sec components, suggesting that interaction was nearest to maximal at this value, it is only at this component duration that matching is predicted by Equation 3 (*i.e.*, when m is nearest to 1.0). Table 4 therefore compares the matching obtained between relative response rate and relative shock-frequency reduction and between relative response rate and relative received shock rate for each of the last six sessions of the different experimental conditions when component duration was 40 sec. It is clear from these data that relative received shock rates are not only far more variable than relative shock-frequency reduction, but also deviate more from the relative response rate. Results of Wilcoxon matched-pairs signed-ranks tests show that relative response rate matched relative shock-frequency reduction significantly better than it matched relative shock rate. For R7, $T = 57.0$, $N = 24$, $p < 0.01$; for R9, $T = 58.0$, $N = 23$, $p < 0.02$; and for R11, $T = 10.0$, $N = 12$, $p < 0.02$ (all p-values for two-tailed tests). Although all of the assumptions of the Wilcoxon test are not fully met by these data, since relative received shock rate and shock-frequency reduction are not strictly independent measures, the test does provide useful information.

If the parameters k and r_0 do not change as component duration shortens, Equation 3 predicts that as m approaches 1.0, response rate in both components of the multiple schedule should decrease. Response rates for a particular component schedule in the present experiment should therefore be lowest when component duration was 40-sec, *i.e.*, when interaction was greatest and matching was obtained. Table 2 shows that this prediction holds true for R7 for two of three different multiple schedules, and for R9 for one of two different multiple schedules. The opposite relation between response rate and component duration was found for R11 for two different schedules. However, the effect predicted by Equation 3 is confounded in this experiment by the effects of prolonged adaptation to electric shock. Such adaptation is most marked in the case of R9, where there is a large decrease in response rate by the last two experimental conditions. For R7 and R9, adaptation effects worked in the same direction as the effects of increased reinforcement interaction, but in the case of R11, adaptation worked against the effect predicted by the equation.

DISCUSSION

The quantitative results of these two experiments, together with those of de Villiers (1972) demonstrate a lawful relationship between response rate and shock-frequency reduction on VI and RI avoidance schedules. Indeed, they suggest that the quantitative relationship between response rate and reinforcement frequency is the same for both positive and negative reinforcement. Herrnstein's (1970) equation for single VI schedules accounts for the relationship between response rate and rein forcement rate on both VI schedules of food reinforcement (Catania and Reynolds, 1968) and VI schedules of shock avoidance. Asymptotic relative response rate on multiple VI schedules with brief components matches relative reinforcement frequency when that reinforcement is either food (Shimp and Wheatley, 1971; Todorov, 1972) or shock-frequency reduction. The relationship between relative response rate and relative shock-frequency re-

Table 4

Session-by-session comparison between relative response rate, relative received shock rate, and relative shock-frequency reduction for each condition with 40-sec components.

Schedule	*Session*	*Relative Response Rate*	*Relative Shock Frequency Reduction*	*Deviation from Matching*	*Relative Shock Rate*	*Deviation from Matching*
R 7						
Multiple	10	0.706	0.670	+0.036	0.602	+0.104
VI 20-sec VI 40-sec	11	0.738	0.655	+0.083	0.682	+0.056
40-sec Components	12	0.705	0.696	+0.009	0.580	+0.125
	13	0.719	0.665	+0.054	0.625	+0.094
	14	0.713	0.663	+0.050	0.632	+0.081
	15	0.703	0.672	+0.031	0.644	+0.059
Multiple	10	0.654	0.680	−0.026	0.616	+0.038
VI 20-sec VI 40-sec	11	0.718	0.686	+0.032	0.609	+0.109
40-sec Components	12	0.718	0.647	+0.071	0.725	−0.007
	13	0.675	0.669	+0.006	0.652	+0.023
	14	0.668	0.665	+0.003	0.624	+0.044
	15	0.679	0.652	+0.027	0.672	+0.007
Multiple	16	0.325	0.338	−0.013	0.364	−0.039
VI 40-sec VI 20-sec	17	0.367	0.302	+0.065	0.449	−0.082
40-sec Components	18	0.347	0.348	−0.001	0.366	−0.019
	19	0.348	0.322	+0.026	0.395	−0.047
	20	0.329	0.335	−0.006	0.314	+0.015
	21	0.341	0.324	+0.017	0.458	−0.117
Multiple	16	0.251	0.242	+0.009	0.414	−0.163
VI 45-sec VI 15-sec	17	0.311	0.240	+0.071	0.340	−0.029
40-sec Components	18	0.306	0.246	+0.060	0.347	−0.041
	19	0.289	0.242	+0.047	0.376	−0.087
	20	0.295	0.244	+0.051	0.354	−0.059
	21	0.240	0.250	−0.010	0.369	−0.129
Mean Deviation from Matching (Disregarding Sign)				0.033		0.066
R 9						
Multiple	10	0.707	0.673	+0.034	0.612	+0.095
VI 20-sec VI 40-sec	11	0.652	0.646	+0.006	0.622	+0.030
40-sec Components	12	0.689	0.686	+0.003	0.563	+0.126
	13	0.659	0.684	−0.025	0.591	+0.068
	14	0.634	0.651	−0.017	0.689	−0.055
	15	0.644	0.663	−0.019	0.615	+0.029
Multiple	10	0.620	0.639	−0.019	0.667	−0.047
VI 20-sec VI 40-sec	11	0.641	0.664	−0.023	0.633	+0.008
40-sec Components	12	0.639	0.663	−0.024	0.633	+0.006
	13	0.662	0.666	−0.004	0.658	+0.004
	14	0.667	0.668	−0.001	0.707	−0.040
	15	0.664	0.647	+0.017	0.662	+0.002
Multiple	16	0.317	0.337	−0.020	0.342	−0.025
VI 40-sec VI 20-sec	17	0.326	0.346	−0.020	0.315	+0.011
40-sec Components	18	0.312	0.337	−0.025	0.403	−0.091
	19	0.335	0.342	−0.007	0.361	−0.026
	20	0.306	0.333	−0.027	0.408	−0.102
	21	0.316	0.342	−0.026	0.435	−0.119
Multiple	16	0.282	0.254	+0.028	0.273	+0.009
VI 45-sec VI 15-sec	17	0.304	0.278	+0.026	0.189	+0.115
40-sec Components	18	0.245	0.225	+0.020	0.356	−0.111
	19	0.226	0.274	−0.048	0.228	−0.002
	20	0.215	0.262	−0.047	0.238	−0.023
	21	0.254	0.272	−0.018	0.237	+0.017
Mean Deviation from Matching				0.021		0.048

Table 4 *continued*

Schedule	*Session*	*Relative Response Rate*	*Relative Shock Frequency Reduction*	*Deviation from Matching*	*Relative Shock Rate*	*Deviation from Matching*
R 11						
Multiple	16	0.381	0.347	+0.034	0.317	+0.064
VI 40-sec VI 20-sec	17	0.386	0.334	+0.052	0.318	+0.068
40-sec Components	18	0.394	0.340	+0.054	0.447	−0.053
	19	0.355	0.331	+0.024	0.300	+0.055
	20	0.374	0.331	+0.043	0.396	−0.024
	21	0.324	0.331	−0.007	0.466	−0.142
Multiple	16	0.270	0.251	+0.019	0.350	−0.080
VI 45-sec VI 15-sec	17	0.257	0.236	+0.021	0.261	−0.004
	18	0.201	0.246	−0.045	0.325	−0.124
	19	0.184	0.258	−0.074	0.262	−0.078
	20	0.236	0.241	−0.005	0.366	−0.130
	21	0.250	0.256	−0.006	0.212	+0.038
		Mean Deviation from Matching		0.032		0.072

duction showed the same changes with decreasing component duration as those found for positive reinforcement (Shimp and Wheatley, 1971; Todorov, 1972). The closest approximation to matching occurred at the component duration for which relative response rate was maximal. With longer and shorter components, relative response rate was lower and undermatching was obtained (*i.e.*, m < 1.0).

In contrast, the relationship between relative response rate and relative received shock rate did not show this pattern of changes. For many conditions, the closest approximation to matching was obtained with longer or shorter component durations than that at which maximal relative response rate occurred. Nevertheless, in both of the present experiments, received shock rate accounted for the data reasonably well. Response rate increased with increasing rate of shock received, and an approximate match between relative response rates and relative received shock rates was observed.

Such a direct relationship between response rate and received shock rate might be explained by avoidance responses directly elicited by the shock. Bolles (1971, 1972) suggested that an animal learns lever pressing as an avoidance response by freezing on the lever when attempts to escape from the box are punished by shock. The animal then reflexively lurches at the lever when shocks are presented, either escaping or postponing the shock. These post-shock elicited responses must be permitted to postpone shock for an avoidance response to be acquired in a free-operant (Sidman) avoidance procedure. It is only as fear dissipates that the response repertoire broadens and inter-shock responding emerges (Bolles, 1972). It should be noted that Bolles is concerned with the acquisition of the avoidance response, and not with its long-term maintenance; nevertheless, it could be argued that the extra responses found in these experiments with increasing received shock rate came from these post-shock response bursts. This could produce a direct relationship between response rate and shock rate. The cumulative records in Figure 1, however, show that little of the responding on the VI avoidance schedules can be accounted for by these bursts.

The apparent relationship between response rate and received shock rate is more plausibly explained by the correlation between shock-frequency reduction and received shock rate. When the VI avoidance schedule is shortened so that shocks are scheduled more frequently, both shock-frequency reduction and obtained shock rate increase. Shock-frequency reduction increases because there are now more opportunities for avoiding the scheduled shocks; received shock rate increases because there are more shorter scheduled inter-shock intervals in which the animal fails to respond. Since the two measures covary to this extent, it is not surprising that if one measure accounts for the data very well, the other should also provide a reasonable fit. Nevertheless, both in these experiments, and in the earlier experiments by de Villiers (1972), shock-frequency reduction provided a more accurate description of the rate of avoidance responding than did received shock rate.

In brief, if shock-frequency reduction is taken as the reinforcer for avoidance, Herrnstein's (1970) analysis of the law of effect provides a means of integrating both positive and negative reinforcement effects on response strength within the same quantitative framework.

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