

# Concurrent schedule responding as a function of body weight

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Five pigeons pecked for food reinforcement on several concurrent schedules. Their body weights were varied from 80% to 110% of their free-feeding weights. A number of predictions of the equations proposed by Herrnstein (1970) were tested. As predicted, the relative rate of responding equalled the relative rate of reinforcement for all subjects, on all schedules, at all body weights. And, as predicted, the overall rates of responding on the components of a concurrent schedule were slower than the local rates of responding on the components of an identical multiple schedule. Contrary to prediction, the total rate of responding generated by the concurrent schedules did not increase with increases in the total rate of reinforcement they provided. And, contrary to prediction, the  $k$  parameter did not remain constant, and the  $R_0$  parameter did not increase with increases in body weight. It was concluded that Herrnstein's matching law and his interpretation of the  $m$  parameter are correct but that the interpretations of  $k$  and  $R_0$  require further investigation.

Most quantitative formulations of the behavior generated by schedules of reinforcement have been based on the performance observed in three types of schedules. The first, the variable interval schedule (VI), reinforces a response emitted after a variable interval of time has elapsed since the last reinforcement. The second and third schedules, the concurrent VI VI and the multiple VI VI schedules, are combinations of two or more variable interval schedules. In a concurrent schedule, the VI component schedules are always available to the subject. The subject can respond on either at any time. In a multiple schedule, the VI component schedules become available successively. The experimenter, not the subject, determines which schedule is presented.

Herrnstein (1970) proposed an equation to describe the absolute rate of responding generated by variable interval schedules. His formula appears in Equation 1.

$$P_1 = \frac{k R_1}{R_1 + mR_2 + R_0} \quad (1)$$

In this equation,  $P_1$  is the rate of responding on the schedule which provides a rate of reinforcement equal to  $R_1$ .  $R_2$  is the rate of reinforcement provided by responding on the alternative schedule, if one is available. And,  $k$ ,  $m$ , and  $R_0$  are parameters estimated from the data.

This research was conducted while the author was a graduate student at Harvard University. It was supported by National Science Foundation and National Institute of Mental Health Predoctoral Fellowships. The author wishes to thank Dr. W. M. Baum for suggesting the parameter estimation techniques, Dr. R. J. Herrnstein for suggesting a number of the ideas which led to the study, and Mrs. A. Papp and Mrs. V. Upham for their assistance in running the subjects. Reprints may be obtained from the author, Department of Psychology, Washington State University, Pullman, Washington.

Equation 1 applies to schedules which appear individually or as components of concurrent and multiple schedules. But, the rates of responding and reinforcement are calculated in different ways for the different schedules. The rates which enter the calculations for concurrent schedules are overall rates. They are calculated by dividing the number of responses emitted, or the number of reinforcers obtained, on each component by the total length of the experimental session. The rates for multiple schedules are local rates. They are calculated by dividing the number of responses or reinforcers on each component by the time for which that component is available. The rates may be calculated in either way for variable interval schedules. The total session time equals the time for which the component is available, because there is only one component schedule.

A large number of findings can be described by an equation with three free parameters. Therefore, Herrnstein has placed restrictions on the values that  $k$ ,  $m$ , and  $R_0$  can take.  $R_0$  represents the rate of reinforcement which the subject obtains from sources which the experimenter has not explicitly programmed (Herrnstein, 1970). Thus, its value should change in an orderly way with changes in several variables. For example, Herrnstein and Loveland (1974) argued that the value of  $R_0$  should increase as the subjects' need for the programmed reinforcer decreases. They assumed that subjects will turn increasingly to other sources of reinforcement as they become satiated for the programmed one.

$k$  varies only with the subject and the units of measurement (Herrnstein, 1974). Otherwise, it is a constant which describes the total amount of behavior generated by the subject. That is,  $k = P_1 + P_2 + P_0$ , where  $P_0$  is the rate of responding generated by the reinforcer,  $R_0$ . Because negative peck rates have no

status, as yet, in Herrnstein's equations,  $k$  must always be greater than  $P_1 + P_2$ .

$m$ , which represents the degree of interaction between the available sources of reinforcement, can take values between 0 and 1.0. It has a value of 1.0 for concurrent schedules in which the alternate sources of reinforcement are available at the same time, but its value is smaller (i.e.,  $0 \leq m \leq 1.0$ ) for multiple schedules in which the alternatives are not simultaneously available (Herrnstein, 1970).

Equations which describe the relative rates of responding on each component of concurrent and multiple schedules have been derived from Equation 1 and from the assumptions about  $m$  (Herrnstein, 1970). The first of these, the matching law, states that the relative rate of responding on either component of a concurrent schedule equals the relative rate of reinforcement it provides. Its derivation, which appears in Equation 2, requires the additional assumption that the values of  $k$  and  $R_0$  are identical for the two component schedules.

$$\frac{P_1}{P_1 + P_2} = \frac{\frac{kR_1}{R_1 + R_2 + R_0}}{\frac{kR_1}{R_1 + R_2 + R_0} + \frac{kR_2}{R_1 + R_2 + R_0}} = \frac{R_1}{R_1 + R_2} \quad (2)$$

The more complex formula which describes the relative rate of responding on each component of a multiple schedule appears in Equation 3.

$$\frac{P_1}{P_1 + P_2} = \frac{\frac{kR_1}{R_1 + mR_2 + R_0}}{\frac{kR_1}{R_1 + mR_2 + R_0} + \frac{kR_2}{mR_1 + R_2 + R_0}} \neq \frac{R_1}{R_1 + R_2} \quad (3)$$

These equations, and the descriptions of their parameters, commit Herrnstein to a number of very specific predictions. First, the descriptions of the  $k$  and  $R_0$  parameters predict that  $k$  should remain constant but  $R_0$  should increase with decreases in the hunger of subjects pecking for food reinforcement. As mentioned earlier, the description of  $k$  requires that it remain a constant, greater than  $P_1 + P_2$ , at all levels of drive. But, Herrnstein and Loveland's interpretation of  $R_0$  requires that it increase with decreases in the subjects' drive for the programmed reinforcer.

Second, the total rate of responding on a concurrent schedule should usually increase with increases in the total rate of reinforcement. The formula for the total rate of responding, generated by a concurrent schedule, appears in Equation 4.

$$P_1 + P_2 = \frac{k(R_1 + R_2)}{R_1 + R_2 + R_0} \quad (4)$$

Increases will not occur if  $R_0 = 0$  or if  $R_0$  is very large compared to  $(R_1 + R_2)$ . If  $R_0 = 0$ ; then  $P_1 + P_2 = k$ , which does not depend on  $R_1 + R_2$ . If  $R_0$  is very large, then the effect of  $R_1 + R_2$  may be too small to detect. But, for intermediate values of  $R_0$ , increasing the size of  $R_1 + R_2$  should mean that an increasingly large fraction of  $k$  will be expressed as instrumental responding,  $P_1 + P_2$ .

Third, Equation 1 and the interpretation of  $m$  predict that the local rate of responding on a variable interval component of a multiple schedule should be greater than the overall rate of responding on the same variable interval component of a concurrent schedule. Equation 1 describes the absolute rate of responding generated by the components of both concurrent and multiple schedules. The formula is applied identically to the two schedules, except for the difference in the way rates are calculated. But, the size of the  $m$  parameter is smaller for multiple schedules. Thus,  $m$  decreases the size of the denominator of the multiple equation relative to the size of its concurrent counterpart. This decrease in the size of the denominator will be expressed as an increase in the size of the predicted rate of responding.

Fourth, Equation 1 predicts that the difference between the overall rates of responding generated by a concurrent schedule, and the local rates generated by an identical multiple schedule, will be greater for the component schedule which provides the lower rate of reinforcement (the less favorable component). Equation 1 shows that the effect of  $m$  will be larger when it multiplies a higher rate of reinforcement.  $m$  will multiply a larger number for the less favorable component because it always multiplies the rate of reinforcement provided by the other component schedule.

Fifth, Equations 2 and 3 predict that deviations from the matching law should occur randomly for concurrent schedules but systematically for multiple schedules. According to Equation 2, the relative rate of responding on either component of a concurrent schedule should always equal its relative rate of reinforcement. Therefore, deviations from equality should occur at random. Changes in variables, such as body weight and rate of reinforcement, should not systematically change how closely the two statistics approach each other. Moreover, the relative rate of responding should exceed its relative rate of reinforcement approximately as often as it falls short of it.

According to Equation 3, deviations from the matching law should occur systematically for multiple schedules. The relative rate of responding generated by the more favorable component schedule should always be less than the relative rate of reinforcement it provides. As argued before, the fractional  $m$  reduces the size of the denominator of the less favorable schedule more than it reduces the denominator of the more favorable schedule. This larger decrease in the



method. Subjects were run until their rate of responding had stabilized at each weight.

When the concurrent VI 1-min VI 4-min schedule had been completed for all weights, the procedure was repeated for a concurrent VI 30-sec VI 2-min schedule. The VI 30-sec schedule was associated with the red key and the VI 2-min schedule with the white key. The same apparatus and sequence of increasing body weights were used. A descending sequence of weights was not run for this schedule. The rates of responding generated by the ascending and descending order of the concurrent VI 1-min VI 4-min schedule had always fallen within  $\pm 5\%$  of each other. Sessions lasted until 40 3.5-sec reinforcers had been collected. Again, a 2.5-sec changeover delay was initiated by all switches from one key to another.

When the concurrent VI 2-min VI 30-sec schedule was completed, a concurrent VI 1.5-min VI 6-min schedule was run for subjects at 80% and then 105% free-feeding weight. This schedule was followed by a concurrent VI 2-min VI 8-min schedule, also run at 80% and 105% free-feeding body weight. The VI 1.5-min and the VI 2-min component schedules were associated with the red key. The VI 6-min and VI 8-min component schedules were associated with the white key. Again, sessions lasted until 40 3.5-sec reinforcers had been collected and a 2.5-sec changeover delay was initiated by all switches from one key to another.

## RESULTS

Table 1 presents the overall rate of responding and the overall rate of reinforcement generated by each subject, on each schedule, at each body weight. The rates are the means of the last 10 days of responding on each schedule. The statistics for 80%, 95%, and 105% body weight, the concurrent VI 1-min VI 4-min schedule, are the means of the points generated in the ascending and descending sequences. The total rate of responding generated by the concurrent schedules does not increase with increases in the total rate of reinforcement they provide.

Figure 1 presents the overall rates of responding generated by the two components of the concurrent VI 1-min VI 4-min schedule as a function of body weight. Each set of coordinates represents an individual subject. The local rates of responding generated by the two components of the multiple VI 1-min VI 4-min schedule reported by Herrnstein and Loveland (1974) have also been plotted.

As predicted, the local rate of responding generated by a variable interval component of a multiple schedule was greater than the overall rate of responding generated by the same variable interval component of a concurrent schedule. Thirty of the 38 local rates of responding generated by the components of the multiple schedule were greater than the overall rates generated by their corresponding concurrent components. This difference is significant beyond the .05 level by the binomial test (Siegel, 1956). Also, as predicted, the differences between the rates of responding generated by the concurrent and multiple schedules were greater for the components which supplied the lower rate of reinforcement.

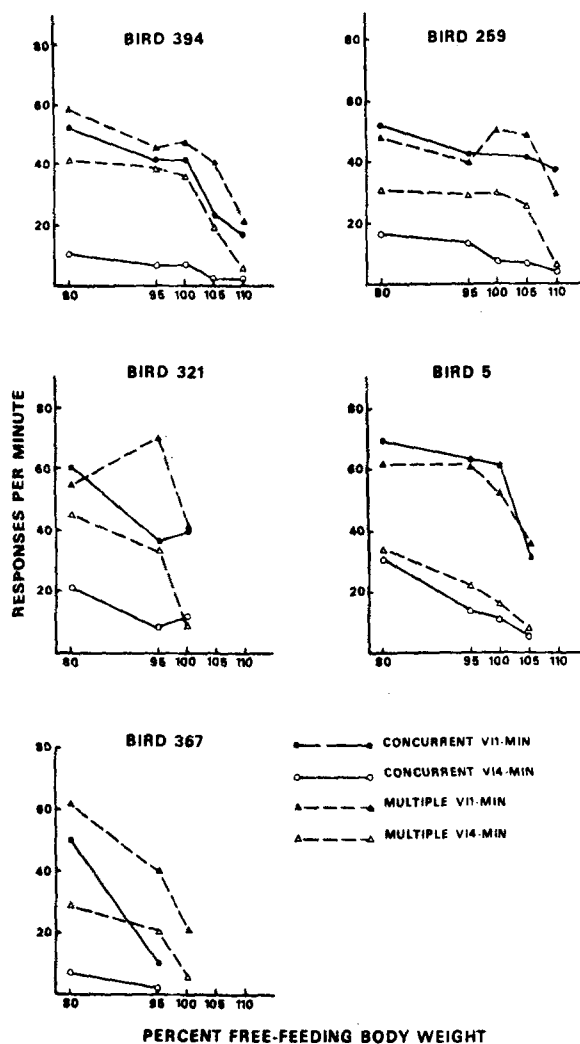


Figure 1. The overall rates of responding on the components of a concurrent VI 1-min VI 4-min schedule and the local rates of responding on the components of a multiple VI 1-min VI 4-min schedule as a function of body weight. (The data for local rates of responding are reproduced from Herrnstein and Loveland. Copyright 1974 by the Society for the Experimental Analysis of Behavior.)

Table 2 presents the relative rate of responding and the relative rate of reinforcement generated by the more favorable component of each concurrent schedule. Again, each statistic represents the mean of the last 10 days of responding on each schedule. This table shows that concurrent responding does obey the matching law and that deviations do occur at random. First, the relative rate of responding falls within 5% of the relative rate of reinforcement for 39 of the 50 points. Second, although the relative rate of responding falls short of its relative rate of reinforcement more often than it exceeds it, the difference is not significant at the .05 level by the binomial test. Third, the size of the difference between the relative rate of responding and its relative rate of reinforcement does not change systematically with

**Table 2**  
Relative Rates of Responding and Relative Rate of Reinforcement on the Component Schedule Providing the Higher Rate of Reinforcement for Each Bird at Each Body Weight on Each Concurrent Schedule

W*	VI 30- Sec		VI 2- Min		VI 1- Min		VI 4- Min		VI 1.5- Min		VI 6- Min		VI 2- Min		VI 8- Min		
	Pecks	SR	Pecks	SR	Pecks	SR	Pecks	SR	Pecks	SR	Pecks	SR	Pecks	SR	Pecks	SR	
<b>Bird 394</b>																	
80	.77	.78	.83	.81	.84	.83	.86	.81									
95	.75	.80	.87	.86													
100	.77	.76	.86	.83													
105	.83	.84	.93	.89	.81	.82	.79	.82									
110	.82	.87	.92	.87													
<b>Bird 259</b>																	
80	.76	.86	.76	.80	.84	.83	.80	.80									
95	.83	.84	.74	.80													
100	.93	.91	.85	.84													
105	.79	.84	.88	.85	.81	.80	.79	.82									
110	.90	.92	.89	.83													
<b>Bird 321</b>																	
80	.82	.86	.73	.82													
95	.75	.81	.81	.83													
100	.85	.87	.78	.83													
<b>Bird 5</b>																	
80	.74	.80	.69	.77	.76	.80	.78	.81									
95	.81	.82	.81	.81													
100	.86	.85	.83	.83													
105	.79	.80	.85	.89	.76	.82	.77	.83									
<b>Bird 367</b>																	
80	.72	.80	.87	.77													
95	.80	.87	.91	.93													

\*Weight

changes in body weight. The size of the difference increases 15 times with increases to the next higher weight, but it decreases 13 times and remains the same 6 times. Fourth, the size of the difference between the two statistics does not change systematically with changes in the rate of reinforcement. The size of the difference increases 13 times with increases to the next higher rate of reinforcement, but it decreases 15 times and remains the same three times.

One method of estimating the k and R<sub>0</sub> parameters uses a modification of a technique proposed by Cohen (1973) for single schedules. If Equation 4 is inverted, the straight line presented in Equation 5 results.

$$\frac{1}{P_1 + P_2} = \frac{R_0}{k} \left( \frac{1}{R_1 + R_2} \right) + \frac{1}{k} \quad (5)$$

Thus, k can be estimated from the y intercept and R<sub>0</sub> from the slope of the function relating the inverse of the total rate of responding to the inverse of the total rate of reinforcement. The function itself can be determined by using a least squares curve fitting technique.

Table 3 contains the k and R<sub>0</sub> parameters estimated by this technique. The parameters have been estimated

**Table 3**  
K and R<sub>0</sub> Parameters for Birds 394, 259, and 5 at 80% and 105% Free-Feeding Weight

Bird	Parameter	Percentage Free-Feeding Body Weight	
		80	105
394	K	69.4	16.0
	R <sub>0</sub>	.9	-28.6
259	K	101.0	36.9
	R <sub>0</sub>	57.4	-5.0
5	K	66.2	42.4
	R <sub>0</sub>	-2.4	3.9

only for those subjects and body weights for which at least four points were available. The results do not fit Herrnstein's predictions. k is not constant but decreases with increases in body weight for all three subjects, and k is less than P<sub>1</sub> + P<sub>2</sub> for five of the six points. R<sub>0</sub> varies erratically: it does not increase with increases in body weight, and negative R<sub>0</sub>s do occur.

The best fitting ks and R<sub>0</sub>s presented in Table 3 leave a disorderly theory. However, Herrnstein's suggestion that k is constant might restore order. It might be possible to find a constant k for each subject which fits the data well and which produces an orderly increase in R<sub>0</sub> as body weight increases.

Finding such a k requires a parameter estimation technique which incorporates either k or R<sub>0</sub> into the independent variable. The incorporated parameter could then be varied until the desired ks were found. One such technique takes the log of both sides of Equation 1. If Equation 1 fit the data perfectly, then plotting log P<sub>1</sub> as a function of log [R<sub>1</sub>/(R<sub>1</sub> + R<sub>2</sub> + R<sub>0</sub>)] would yield a straight line with a slope equal to 1.0 and a y intercept equal to log k for some choice of R<sub>0</sub>.

Table 4 shows that it is possible to find the desired ks and R<sub>0</sub>s by this technique. A constant k may be found for each subject which produces an orderly increase in

**Table 4**  
Constant Ks, Their Ros, Slopes, and the Proportion of the Variance Accounted for, for Birds 394, 259, and 5 at 80% and 105% Free-Feeding Weight

Bird	Parameter	Percentage Free-Feeding Body Weight	
		80	105
394	K	75.0	75.0
	R <sub>0</sub>	2.8	32.6
	Slope	1.08	1.06
	Proportion of Variance	.99	.81
259	K	70.0	70.0
	R <sub>0</sub>	20.0	50.0
	Slope	1.01	.93
	Proportion of Variance	.94	.91
5	K	100.0	100.0
	R <sub>0</sub>	68.0	165.0
	Slope	.71	.70
	Proportion of Variance	.77	.75

$R_0$  with increases in body weight and which fits Equation 1 well.  $R_0$  was varied from  $-100$  to  $+2,000$  for each subject, in order to insure that these parameters were not local minima.

The constant  $k$ s and their  $R_0$ s presented in Table 4 fit the data only slightly more poorly than the single best fitting  $k$ s and  $R_0$ s estimated by this technique. The mean slopes of the lines which produced the constant  $k$ s are 1.07, .97, and .71 for Birds 394, 259, and 5, respectively. The corresponding mean slopes for the best fitting parameters were 1.00, .98, and .91, respectively. The mean proportion of the variance accounted for by the line which produced the constant  $k$ s was .90, .93, and .76 for Birds 394, 259, and 5, respectively. The corresponding mean proportion of the variance accounted for by the best fitting parameters was .98, .97, and .89.

## DISCUSSION

The data do not directly confirm the first and second predictions of Herrnstein's theory. Table 3 contradicts the first prediction, that  $k$  remains constant and  $R_0$  decreases as body weight increases. However, Table 4 supports this prediction.  $R_0$  does decrease with increases in body weight when  $k$  is held constant.

The present results cannot dismiss either of these interpretations of the data. On the one hand, a  $k$  that decreases with increases in body weight does fit the data better. On the other hand, the constant  $k$  assumption does lead to a neater theory without substantially reducing the fit of the theory to the data.

Table 1 contradicts the second prediction, that the total rate of responding will increase with increases in the total rate of reinforcement. Again, there are two possible interpretations of this finding. The first argues that the data presented in Table 1 are correct. The total rate of responding on two-key concurrent schedules does not increase with increases in the total rate of reinforcement. This interpretation is supported by the results of studies by Fantino, Squires, Delbrück, and Peterson (1972) and by McSweeney (1975). Fantino et al. did not find an increase in the total rate of responding on a two-key concurrent schedule when the total rate of reinforcement varied from 9 to 900 reinforcers per hour. The subjects were pigeons pecking keys for food reinforcement. McSweeney did not find an increase in the total rate of responding on a two-treadle concurrent schedule when the total rate of reinforcement varied from 45 to 150 reinforcers per hour. The subjects were pigeons pressing treadles for food reinforcement.

The second interpretation argues that irrelevant variables obscured an orderly increase in the rate of responding, which would have occurred otherwise. The lengthy manipulations of body weight which intervened between successive variations in the rate of reinforcement may have introduced these variables. Equation 4 may support this argument. It shows that the

size of the increase in the rate of responding would be small over the range of rates of reinforcement and the values of  $k$  and  $R_0$  found here. A change of only 10 to 15 pecks per minute would be expected. And, such a small change could be obscured by fluctuations in irrelevant variables.

Studies by Findley (1958) and Cantania (1963) may also support this interpretation. Both of these studies found orderly increases in the total rate of responding with increases in the total rate of reinforcement. However, Findley and Cantania both used procedures which differ from the ones used in the present study and in the studies by Fantino et al. (1972) and McSweeney (1975). They used Findley concurrent procedures. The Findley procedure presents the component schedules on the same manipulandum. The subject changes schedule by responding on a second manipulandum. The present study, and the studies by Fantino et al. and McSweeney, used two-key concurrent procedures. The two-key procedure presents the component schedules on two different manipulanda. The subjects change from one component to the other by moving from one manipulandum to the other. Herrnstein's equations might describe the behavior generated by Findley concurrent schedules without describing the behaviors generated by the present two-key concurrents.

The first two predictions of Herrnstein's equations deserve further study. Both predictions follow from Herrnstein's assumptions about  $k$  and  $R_0$ . If further studies also reject these predictions, then the interpretations of  $k$  and  $R_0$  must be revised or Herrnstein's equations must be restricted to the behavior generated by multiple and Findley concurrent schedules. Further studies should begin with a replication of the present experiment with two differences in procedure. First, a wider range of total rates of reinforcement should be used. A wider range of reinforcement would make the change in the total rate of responding easier to detect by making it larger. Second, all of the schedules of reinforcement should be conducted at each body weight before proceeding to the next weight. This would decrease the probability that irrelevant variables obscured the results.

Other studies might manipulate the size of  $R_0$  by presenting extra reinforcers to the subject. For example, a subject, responding on a concurrent schedule for food reinforcement, might be given access to an activity wheel for part of the total session time. The size of  $R_0$  could be manipulated by changing the amount of time for which the wheel was available. If Herrnstein's equations are correct, and if the total rate of reinforcement was also manipulated, then the inverse of the total rate of responding should be a linear function of the inverse of the total rate of reinforcement, as shown in Equation 5. Increasing  $R_0$  should increase the slope of this function. But the  $y$  intercept, which is the inverse of  $k$ , should remain the same regardless of the size of  $R_0$ .

The data confirm Herrnstein's interpretation of the m

parameter. The third, fourth, and fifth predictions of Herrnstein's equations follow from the assumption that  $m = 1.0$  for concurrent schedules, but  $0 \leq m \leq 1$  for multiple schedules. All of these predictions are confirmed.

Figure 1 confirms the third and fourth predictions. The local rates of responding generated by the components of the multiple VI 1-min VI 4-min schedule are greater than the overall rates of responding generated by the components of the concurrent VI 1-min VI 4-min schedule. And, the differences between the local rates of responding on the multiple schedule and the overall rates of responding on the concurrent schedules are greater for the component schedules which provide the lower rates of reinforcement.

Table 2 and the results of Herrnstein and Loveland (1974) support the fifth prediction. Deviations from the matching law do occur randomly for concurrent schedules, but they occur systematically for multiple schedules. Table 2 presents the results for concurrent schedules. Concurrent schedule responding does obey the matching law, and deviations from this law do occur randomly. The relative rates of responding exceed their relative rates of reinforcement approximately as often as they fall short of them. Figure 4 of Herrnstein and Loveland's study presents the results for multiple schedules. All but one of the relative rates of responding, on the component which provided the higher rate of reinforcement, fell short of its relative rate of reinforcement, and the relative rates of responding did approach their relative rates of reinforcement as body weight increased.

Confirmation of the interpretation of the  $m$  parameter must be interpreted carefully, however. Rachlin (1973) has criticized Herrnstein's theory for calculating rates in different ways for the concurrent and multiple schedules. He argues that Herrnstein's equations lead to the conclusion that the only difference between concurrent and multiple schedule responding lies in the  $m$  parameter. The difference in the way rates are calculated hides the fact that two entirely different processes govern responding on the two schedules.

Rachlin cites a study by Killeen (1972) to support his argument. Killeen placed several subjects on a concurrent schedule of reinforcement. When each of these subjects changed from one component schedule to the other, the component schedule available to a second subject also changed. The second subjects, which could not control their own schedule changes, were technically responding on multiple schedules. Killeen reported that the local rate of responding on the concurrent schedule was greater than the local rate of responding on the yoked multiple schedule. And, he reported that subjects adjusted their rates of responding to the rates of reinforcement in different ways for the two schedules. They adjusted their responding to the rates of reinforcement provided by the multiple schedule by changing their local rates of responding. They adjusted their responding to the rates of reinforcement provided

by the concurrent schedule by changing the proportion of the total session time which they spent responding on each component schedule. Their local rates of responding remained unchanged.

Killeen's results do not contradict the present results or Herrnstein's theory. The rate of responding generated by a concurrent schedule could be greater than the rate generated by a multiple schedule when calculated by Killeen's local response rate formula but be less than the multiple rate when calculated by the present overall rate formula. The same number of emitted responses would produce a higher response rate when calculated by the local formula than when calculated by the overall formula. The denominator of the local formula is always smaller than or equal to the denominator of the overall formula because the time spent responding on either one of the component schedules is always less than or equal to the total session time.

However, as Rachlin has observed, Killeen's results do suggest caution in interpreting the present results. Although Herrnstein's prediction is confirmed, this prediction does not support the conclusion that similar processes underly concurrent and multiple schedule responding.

In summary, several predictions of Herrnstein's equations fit the data well. The relative rates of responding on the concurrent schedules suggest that the matching law is correct. The differences between concurrent and multiple schedule responding suggest that the interpretation of the  $m$  parameter is essentially correct. But, the  $k$  and  $R_0$  parameters presented in Tables 3 and 4 suggest that the interpretations of  $k$  and  $R_0$  require further investigation.

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