BEHAVIOR OF HUMANS IN VARIABLE-INTERVAL SCHEDULES OF REINFORCEMENT[1]

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During Phase I, human subjects pressed a button for monetary reinforcement in five variable-interval schedules, each of which specified a different frequency of reinforcement. The rate of responding was an increasing, negatively accelerated function of reinforcement frequency; the data conformed closely to Herrnstein's equation. During Phase II, the same five schedules were in operation, but in addition a concurrent variable-interval schedule (B) was introduced, responses on which were always reinforced at the same frequency. Response rate in component A increased while the response rate in B decreased, as a function of the reinforcement frequency in component A. Relative response rates in the two component schedules matched the relative frequencies of reinforcement. Comparing the absolute response rates in component A during Phase I and Phase II it was found that introduction of the concurrent schedule did not affect the value of the theoretical maximum response rate, but did increase the value of the reinforcement frequency needed to obtain any particular submaximal response rate.

Key words: Herrnstein's equation, response rate, reinforcement frequency, matching law, concurrent schedules, variable interval, button pressing, humans

Herrnstein (1970) proposed an equation of the following form to describe the relationship between response rate and reinforcement frequency in variable-interval (VI) schedules of reinforcement:

$$R_A = R_{max} \cdot r_A/(K_H + r_A) \qquad [1]$$

where R_A is the response rate and r_A the reinforcement frequency. The constant R_{max} expresses the maximum response rate (Herrnstein, 1974), and K_H ('Herrnstein's constant') is the reinforcement frequency corresponding to the half-maximal response rate.[2] Using the data of Catania and Reynolds (1968), Herrnstein (1970) showed that eq. [1], which defines a rectangular hyperbola, accurately describes the behavior of pigeons in VI schedules.

If an organism is exposed to two VI schedules concurrently, the rate of responding in one schedule depends not only on the fre-

quency of reinforcement in that schedule but also on the reinforcement frequency in the other schedule (Catania, 1963). Herrnstein (1970) proposed the following equations to account for the response rates in the two schedules:

$$R_A = R_{max} \cdot r_A/(K_H + r_A + r_B) \qquad [2]$$
$$R_B = R_{max} \cdot r_B/(K_H + r_A + r_B) \qquad [3]$$

where the subscripts A and B designate the two schedules. If the value of r_B is held constant, it follows from eq. [2] that R_A will increase with increasing values of r_A, while it follows from eq. [3] that R_B will decline with increasing values of r_A. These predictions are supported by the findings of Catania (1963). If it is assumed that the values of the constants R_{max} and K_H are invariant between the two schedules, eqs. [2] and [3] may be combined, to yield the following relationship (Herrnstein, 1970):

$$R_A/(R_A + R_B) = r_A/(r_A + r_B) \qquad [4]$$

Equation [4] states that the relative rate of responding in one schedule is equal to the relative frequency of reinforcement delivery in that schedule. This relationship is known as the Matching Law (Herrnstein, 1970), and is well supported by experimental observations (Herrnstein, 1961; Schroeder and Holland,

[2]$r_A = K_H$ when $R = R_{max}/2$ (cf. eq. [5], below). Note that this purely mathematical account of K_H bypasses the controversy that currently surrounds the theoretical significance of this term [cf. Herrnstein's "r_o" (Herrnstein, 1970) and Catania's "C" (Catania, 1973)].

1969; Shull and Pliskoff, 1967; Silberberg and Fantino, 1970; Todorov, 1972).

A further prediction can be derived by comparing eq. [1] with eq. [2]. Since both equations define a rectangular hyperbola that approaches an asymptote at R_{max}, the introduction of a concurrent source of reinforcement should not alter the theoretical maximum response rate, although it will increase the reinforcement frequency needed to obtain the half-maximal response rate:

from eq. [1],

$$R_A = R_{max}/2 \text{ when } r_A = K_H \qquad [5]$$

from eq. [2],

$$R_A = R_{max}/2 \text{ when } r_A = K_H + r_B \qquad [6]$$

The present experiment attempted to determine whether eqs. [1] to [6] are applicable to human operant behavior. Although some examinations of the Matching Law have used human subjects (Baum, 1975; Conger and Killeen, 1974; Schmitt, 1974; Schroeder and Holland, 1969), eqs. [1], [2], and [3] have been verified only in pigeons.

METHOD

Subjects

Four volunteer subjects (two male and two female), aged 20 to 27 yr, were all experimentally naive at the start of training and had had no previous training in psychology (the two

male subjects were technicians, the two female subjects secretaries).

Apparatus

Experimental sessions took place in a small cubicle. The apparatus used is illustrated in Figure 1. The subject sat at a desk facing a sloping panel (40 cm wide and 30 cm in height) on which were mounted five amber lights (lights 'A'), labelled 1 to 5, a green light, and a digital counter. In front of the panel was a button that could be depressed by a force of approximately 6 N (600 g). Auditory response feedback was provided by a relay situated behind the panel. During Phase II (see below, Procedure), a small auxiliary box was also present on the desk. Mounted on this box were a small button, which could be depressed by a force of approximately 1 N (100 g), and an amber light (light 'B').

Conventional electromechanical programming and recording equipment was situated in another room, judged by the experimenters to be out of earshot from the experimental cubicle. Additional masking noise was provided by a radio.

Procedure

Phase I. The subjects were instructed as follows:

This is a situation in which you can earn money. You earn money simply by pressing the button. Sometimes when you
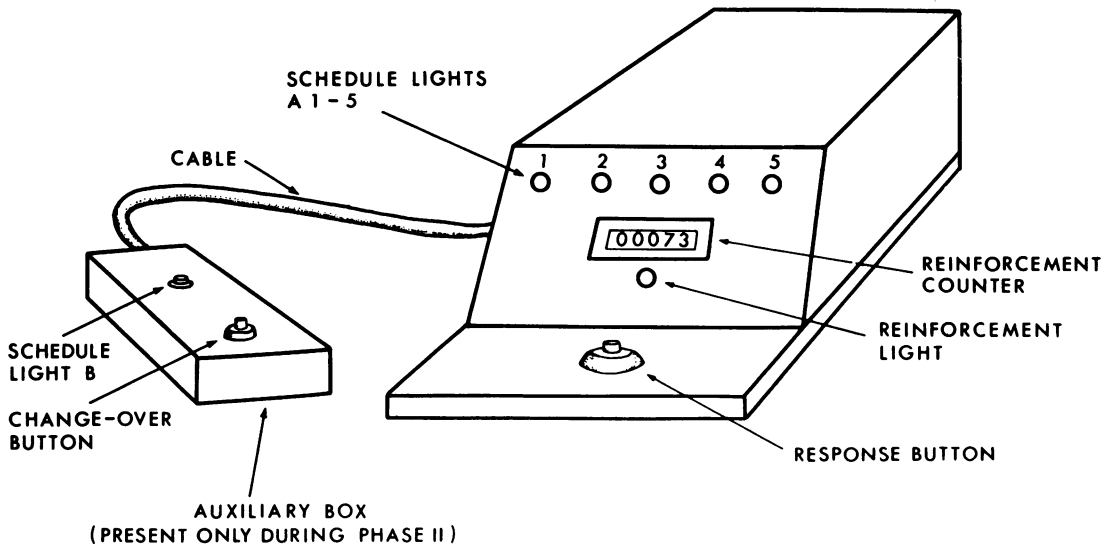

Fig. 1. Diagram of subjects' response panel.

press the button the green light will flash on. This means you will have earned one penny. The total amount of money you have earned is shown on this counter; every time the green light flashes it adds one penny to the total score. When operating the button make sure you press hard enough. You can tell whether you have pressed hard enough by listening for a slight click coming from inside the box. Now look at these orange lights. When one of the orange lights is on, it means that you are able to earn money. At the beginning of the session one of the lights will come on and will stay on for 10 min: throughout this time you can earn money. At the end of 10 minutes the light will go off for 5 minutes and during this time you should rest. After the rest period, another light will come on, again for 10 minutes, and you may earn some more money. Then there will be another rest period, and so on until each of the five orange lights has been presented. At the end of the session we will take the reading from the counter and note down how much you have earned. You will be paid in a lump sum at the end of the experiment.

The five amber lights (A 1 to 5) were each associated with a different VI schedule. Constant probability schedules were used, as described by Catania and Reynolds (1968). The reinforcement frequencies specified by the schedules were as follows: A1, 5 rf/hr (VI 720-sec); A2, 23 rf/hr (VI 157-sec); A3, 70 rf/hr (VI 51-sec); A4, 141 rf/hr (VI 25-sec); A5, 211 rf/hr (VI 17-sec). (Throughout this paper the term "reinforcement frequency" refers to *scheduled* reinforcement frequency. In no case did obtained reinforcement frequency deviate by more than 5% from scheduled reinforcement frequency). Reinforcement consisted of a 150-msec illumination of the green light and the addition of one point to the score displayed on the counter. The five schedules were presented in a quasi-random sequence, with the constraint that each schedule occurred in a different ordinal position on successive days. Experimental sessions took place on 15 successive working days.

Phase II. Phase II was carried out with the two female subjects, who consented to continue with the experiment for a further 15 days. The auxiliary box was shown to the subjects, and its function explained. By pressing the auxiliary (changeover) button, the subject could extinguish whichever 'A' light was illuminated and simultaneously illuminate light 'B' on the auxiliary panel. Light 'B' was associated with a VI schedule identical to that indicated by light A3. No restriction was imposed on the frequency with which subjects could change over from one component to another, and no changeover delay was employed.

RESULTS

Phase I

All four subjects showed stable response rates on the five schedules by the fifth to eighth session, as judged by inspection of the cumulative records and averaged rates. Performance took the form of a high running rate interspersed with brief pauses at irregular intervals. In schedules where lower overall rates were observed (see below), running rate was lower and the pauses somewhat longer.

The mean response rates ($R_A \pm$ s.e.m.) recorded in each schedule during the last five sessions were calculated individually for each subject, and were plotted against reinforcement frequency (r_A). For all four subjects, response rate was an increasing, negatively accelerated function of reinforcement frequency, approaching an asymptote at high values of reinforcement frequency. Rectangular hyperbolae were fitted to the data by computer using nonlinear regression analysis (Wilkinson, 1961). This method gives estimates ($\pm$ s.e.est) of the theoretical maximum response rate (R_{max}) and the reinforcement frequency corresponding to the half-maximal response rate (K_H). Figure 2 (open circles) shows the data obtained from all four subjects; the estimated values of the constants are shown in Table 1. The two male subjects showed higher estimated values of R_{max} than the two female subjects (t test, $p < 0.05$); however, there was no significant difference between the estimated values of K_H obtained from the male and female subjects. The index of determination (p^2) was calculated for the curves obtained from each subject (p^2 expresses the proportion of the variance of the y-values that can be accounted for in terms of x, in a curvilinear function [Lewis, 1960].) The values of p^2 were
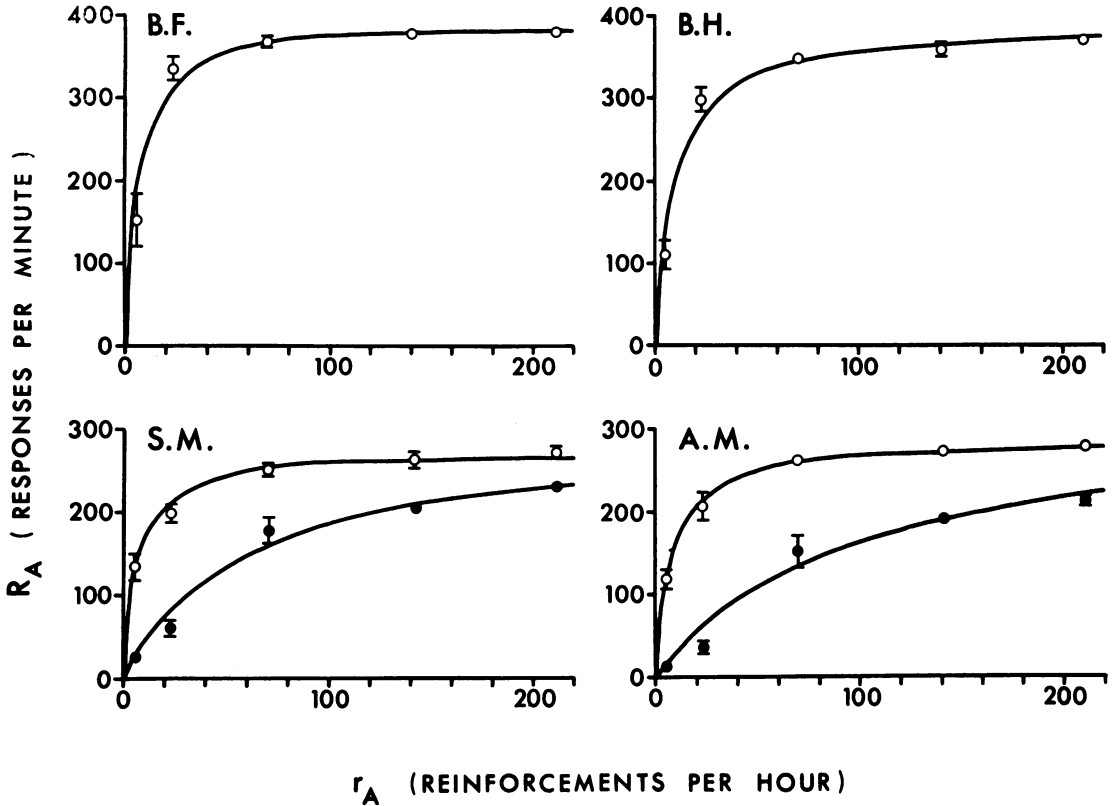
Fig. 2. Relationship between rate of responding in component A (R_A) and reinforcement frequency scheduled for component A (r_A). Upper graphs: data obtained from the two male subjects. Lower graphs: data obtained from the two female subjects. Points are response rates averaged over the last five sessions (vertical bars: ± s.e.m.). Open circles: data obtained during Phase I; closed circles: data obtained during Phase II. Curves are rectangular hyperbolae fitted by nonlinear regression analysis; values of the constants (± s.e.est.) are shown in Table 1.

0.98 (B.H.), 0.96 (B.F.), 0.97 (S.M.) and 0.99 (A.M.).

Phase II

Responding in component A. For both subjects, response rate in component A (R_A) was an increasing, negatively accelerated function of reinforcement frequency scheduled for

component A (r_A) (Figure 3, left-hand graphs, closed circles). Rectangular hyperbolae were fitted to the data by the method of Wilkinson (1961). The values of the constants so obtained are shown in Table 1. The values of p^2 were 0.93 (S.M.) and 0.91 (A.M.).

Responding in component B. For both subjects, the response rate in component B (R_B)

Table 1

Estimated Values of the Constants

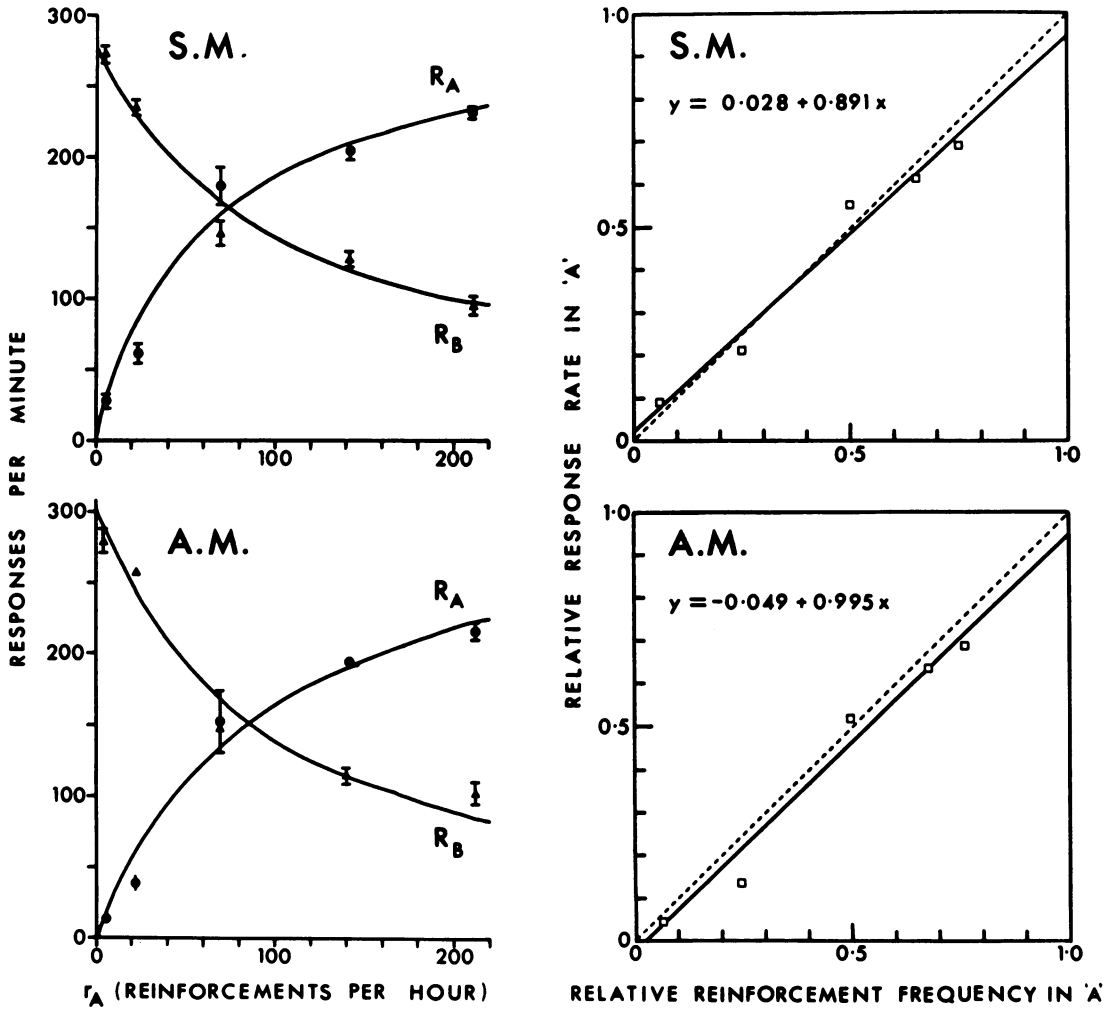| Subject	Maximum Response Rate (resp/min ± s.e.est)		Reinforcement Frequency Corresponding to Half Maximal Response Rate (rft/hr ± s.e.est)	
	Phase I	*Phase II*	*Phase I*	*Phase II*
BH (male)	391.9 (±14.8)	—	9.8 (±2.0)	—
BF (male)	399.2 (±15.4)	—	6.8 (±1.5)	—
SM (female)	270.9 (±8.2)	300.2 (±18.9)	5.8 (±1.1)	62.6 (±12.4)
AM (female)	286.8 (±6.0)	328.2 (±33.2)	7.6 (±0.9)	103.0 (±31.8)

Fig. 3. Absolute and relative response rates in the two components (A and B) during Phase II. *Left-hand graphs:* absolute response rates in component A (R_A, closed circles) and component B (R_B, closed triangles) plotted against reinforcement frequency scheduled for responding in component A (r_A). Points are response rates averaged over last five sessions (vertical bars: ± s.e.m.). Curves for R_A *versus* r_A are rectangular hyperbolae fitted by nonlinear regression analysis; curves for R_B *versus* r_A are of the form defined by eq. [3] (see text for method of curve fitting). *Right-hand graphs:* Same data expressed as relative response rate in component A($R_A/[R_A + R_B]$) *versus* relative reinforcement frequency in component A($r_A/[r_A + r_B]$). Solid lines are best-fit linear regression lines (see equations). Broken lines show ideal matching relationship.

decreased asymptotically with increasing values of r_A. Curves having the form defined by eq. [3] were fitted to the data by nonlinear regression analysis (Wilkinson, 1961). The data from both subjects are shown in Figure 3 (left-hand graphs, closed triangles). The values of p^2 were 0.95 (S.M.) and 0.93 (A.M.).

Relative rates of responding. The right-hand graphs of Figure 3 show, for both subjects, the relative response rates in component A ($R_A/[R_A + R_B]$) as a function of relative

reinforcement frequency in component A ($r_A/[r_A + r_B]$). Straight-line functions were fitted to the data by the method of least squares. The equation for the line was y = 0.028 + 0.891x in the case of SM, and −0.049 + 0.996x in the case of AM. The regression coefficients were 0.980 and 0.981 for the two subjects respectively.

Comparison of response rates in component A during Phase I and Phase II. Figure 2 (lower graphs) shows the curves of R_A *versus* r_A ob-

tained from the two subjects who took part in both phases (open circles: Phase I; closed circles: Phase II). For both, the curve was shifted to the right during Phase II, although the Phase I and Phase II curves appeared to approach the same asymptote. This is confirmed by Table 1, which shows the estimated values of the constants, together with their associated standard errors. For both subjects, the value of r_A corresponding to the half-maximal response rate increased significantly during Phase II (t test, $p < 0.001$); there was no significant change in the value of the maximal response rate itself (t test, $p > 0.1$).

DISCUSSION

The results from Phase I demonstrate that eq. [1] is applicable to human operant behavior, in that the rectangular hyperbolic function provided a good description of the data obtained from all four subjects. It is possible that other asymptotic functions might have provided equally accurate descriptions of the data. However, the choice of the hyperbolic function was based on an existing theoretical framework (Herrnstein, 1970), and our results provide no grounds for rejecting this choice.

During Phase II, the value of r_B was held constant and the value of r_A was varied. For both subjects, R_A increased, while R_B decreased, with increasing values of r_A. These findings are in agreement with the observations of Catania (1963) with pigeons, and suggest that eqs. [2] and [3] may be applied to human subjects.

During Phase II, both subjects showed close matching between relative response rate and relative reinforcement frequency. Previous studies of matching in humans have yielded mixed results. Schroeder and Holland (1969), using a vigilance task, found matching between the proportion of eye-movement responses toward a particular site and the proportion of signals detected at the site. Baum (1975), also using a vigilance task, confirmed the matching relationship when time-allocation rather than response rate was the behavioral measure. Conger and Killeen (1974), who studied social behavior in a small group setting, found matching between the proportion of verbal responses directed toward a particular individual and the proportion of

verbal reinforcements received from that individual. On the other hand, Schmitt (1974), using a button-pressing task and monetary reinforcement, failed to observe matching between relative response rate and relative reinforcement frequency. The present results are in agreement with those of Schroeder and Holland (1969), Baum (1975), and Conger and Killeen (1974). It is of interest that unlike any of the previous studies, the present experiment did not involve the use of changeover delays; it would seem therefore that the use of a changeover delay is not a prerequisite for observing matching in this kind of experiment (see Herrnstein, 1970).

By comparing eq. [1] with eq. [2] the following predictions may be derived: (1) The curves derived from Phase I and Phase II should approach the same asymptote, R_{max}; (2) The reinforcement frequency (r_A) corresponding to the half-maximal response rate should be exactly r_B reinforcements per hour greater during Phase II than during Phase I (*cf.* eqs. [5] and [6]). Table 1 shows that the first of these predictions was confirmed. With respect to the second prediction, S.M. showed an increase in the value of r_A corresponding to $R_{max}/2$ from 5.8 during Phase I to 62.6 during Phase II (a change of 56.8 reinforcements per hour), while A.M. showed an increase from 7.6 during Phase I to 103.0 during Phase II (a change of 95.4 reinforcements per hour). In the present experiment, an increase of 70.0 reinforcements per hour would be predicted (*i.e.*, the value of r_B). For both subjects, the discrepancy between the observed and predicted change in the values of r_A corresponding to $R_{max}/2$, while considerable, was within the limits of error obtained in this experiment (see Table 1).

It is well known that behavioral interaction can occur between the components of a multiple schedule (see Herrnstein, 1970). Since in the present experiment all five schedules occurred in each session, the entire session might be regarded as a five-component multiple schedule in which the individual components were separated by timeout periods. However, several features of the design make it unlikely that interaction between schedules played any systematic role in the results. First, relatively long (5-min) timeout periods were interposed between successive schedules, and there is evidence that the degree of interaction is lessened by temporal separation of the components of

a multiple schedule (Boneau and Axelrod, 1962; Pliskoff, 1963; Wilton and Gay, 1969). Second, rather long (10-min) periods of exposure to each schedule were used, because it has been reported that the degree of interaction decreases as a function of component duration (Shimp and Wheatley, 1971; Todorov, 1972). Third, any systematic ordering effects should have been neutralized by the randomized presentation of the schedules.

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