INCREASING AND SIGNALING BACKGROUND REINFORCEMENT: EFFECT ON THE FOREGROUND RESPONSE–REINFORCER RELATION

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Herrnstein's (1970) hyperbolic matching equation describes the relationship between response rate and reinforcement rate. It has two estimated parameters, *k* and *Re*. According to one interpretation, *k* measures motor performance and *Re* measures the efficacy of the reinforcer maintaining responding relative to background sources of reinforcement. Experiment 1 tested this interpretation of the *Re* parameter by observing the effect of adding and removing an additional source of reinforcement to the context. Using a within-session procedure, estimates of *Re* were obtained from the response-reinforcer relation over a series of seven variable-interval schedules. A second, concurrently available variable-interval schedule of reinforcement was added and then removed from the context. Results showed that when the alternative was added to the context, the value of *Re* increased by 107 reinforcers per hour; this approximated the 91 reinforcers per hour obtained from this schedule. Experiment 2 investigated the effects of signaling background reinforcement on *k* and *Re*. The signal decreased *Re*, but did not have a systematic effect on *k*. In general, the results supported Herrnstein's interpretation that in settings with one experimenter-controlled reinforcement source, *Re* indexes the strength of the reinforcer maintaining responding relative to uncontrolled background sources of reinforcement.
    Key words: Herrnstein's hyperbola, matching law, background reinforcement, signaled reinforcement, lever press, rats

Herrnstein (1970) formulated an elementary matching law equation for the case in which there is only a single measured source of reinforcement and a single measured response rate. The form of that equation is

$$B_1 = \frac{kR_1}{R_1 + Re}, \qquad (1)$$

where B_1 is response rate, R_1 is reinforcement rate, and k and Re are fitted constants. The structural or curve-fitting definitions of the constants reveal the relationship between response rate and reinforcement rate implied by Equation 1. In the numerator, k is an estimate of the response-rate asymptote. For instance, as reinforcement rate increases, response rate approaches but does not exceed k. Thus, k is measured in the same units as the measured behavior (e.g., responses per minute). In the numerator, Re is equal to the rate of reinforcement that maintains a one-half asymptotic response rate. For example, when R_1 is equal to Re, response rate must be equal to $k/2$. Thus, Re is measured in the same units as the experimenter-controlled reinforcer (e.g., 0.10 mL sucrose servings per hour).

On the basis of the matching law, Herrnstein (1970, 1974) provided empirical interpretations of the curve-fitting definitions of k and Re. According to his account, k measures motoric aspects of responding, such as duration of the response, and Re measures background, uncontrolled sources of reinforcement, such as those that accrue from resting, exploring the chamber, and so forth. However, because Re is measured in the units of the arranged reinforcer, the value of Re can change as a function either of operations that directly affect the arranged reinforcer or, alternatively, of operations that directly affect the background reinforcers.

These interpretations have some empirical support. In a review of the literature, Heyman and Monaghan (1987) found that in studies in which Re changed but k did not, the experimenter varied either reinforcement magnitude, reinforcement quality, or deprivation level. In contrast, in studies in which k changed but Re did not, the experimenter manipulated the response requirement. For example, the value of k decreased when the response manipulandum was changed from a key to a treadle

(McSweeney, 1978) or the force required to make a response was increased (Heyman & Monaghan, 1987). Based on this evidence, Heyman and Monaghan concluded that k indexes the response topography of reinforced responses, whereas Re indexes the efficacy of the experimenter-controlled reinforcer relative to background reinforcement.

Although most tests of the interpretation of Re as a source of background reinforcement have taken the form of altering either some aspect of the measured reinforcement or the deprivation level of the subject (de Villiers & Herrnstein, 1976), a few studies have tested the interpretation of Re by attempting to change background sources of reinforcement. Such tests have taken the form of observing changes in the value of Re when an extraneous source of reinforcement is added to the context. In this case, the value of Re is expected to increase, and the magnitude of the change is expected to reflect the rate of reinforcement introduced to the context. Attempts to test the interpretation of Re in this manner have shown qualitative, but not quantitative, support for the predictions of Equation 1. In other words, when reinforcement was added to the background, Re increased; however, the magnitude of the changes either markedly overestimated (Bradshaw, 1977) or underestimated (White, McLean, & Aldiss, 1986) the nominal value.

Bradshaw (1977) trained 4 rats on a series of five variable-interval (VI) schedules. Estimates of k and Re were obtained for this series of schedules. Next, a second VI reinforcement schedule was added to the setting. According to Bradshaw, the rate of reinforcement from this second alternative was 21 reinforcers per hour. Estimates of k and Re were compared with this second source absent from and present in the context. Results showed, as expected, that the value of k remained approximately the same while the value of Re increased. However, the average value of Re increased by 85 reinforcers per hour in the concurrent-alternative condition, whereas the nominal reinforcement from the second alternative was only 21 reinforcers per hour. Thus, the value of Re increased by a substantially greater amount than would be expected based on the scheduled rate of reinforcement added to the context.

White et al. (1986) investigated the effect of different rates of reinforcement from an alternative source on the value of Re using a different procedure. In their experiment, three groups of rats were exposed to a series of VI schedules on one alternative, with a single VI schedule concurrently available on the other alternative. The rates of reinforcement provided by the concurrently available VI schedule varied among groups. The results showed that although the hyperbolic matching equation adequately described the relation between response and reinforcement rates on the variable alternative for each group, the estimates of Re in two of the three groups markedly underestimated the rates of reinforcement from the single VI schedule. Because these estimates of Re presumably reflect reinforcement from both the single VI schedule and background sources of reinforcement, the estimates of Re should have been larger.

In summary, there is some qualitative, but not quantitative, support for this interpretation of Re from studies that manipulated background sources of reinforcement. Bradshaw (1977) found that Re increased with the addition of an alternative source: however, the magnitude of the change exceeded the rate of reinforcement scheduled for that source. Using a different procedure, White et al. (1986) found that Re fell below the rate of reinforcement added to the context.

Based on the assumption that procedural factors may have played a role in these discrepant results, the present study tested this interpretation of Re using a within-session procedure rather than a between-conditions procedure. In previous studies, subjects were exposed to only a single VI schedule or pair of concurrent VI schedules in each session. Once response rates stabilized for the schedule in effect, subjects were advanced to another schedule. After response and reinforcement rates were acquired for each schedule or concurrent set of schedules, k and Re values were estimated.

In contrast, with the within-session procedure used in the present study, subjects experienced an entire series of VI schedules in each session, and stability was defined by the fitted estimates, k and Re from each session. Each session consisted of exposure to a series of VI schedules on one alternative; in choice conditions, each VI schedule was paired with a second VI schedule as the other alternative. This within-session procedure has produced

reliable results in previous studies of environmental (Bradshaw, Szabadi, & Bevan, 1976, 1979; Heyman & Monaghan, 1987; Petry & Heyman, 1994) and pharmacological (Hamilton, Stellar, & Hart, 1985; Heyman, 1983, 1992; Heyman, Kinzie, & Seiden, 1986) manipulations of reinforcement efficacy.

One advantage of this procedure is that it controls for changes as a function of the passage of time because subjects experience all schedules in each session rather than just one schedule in each condition. Second, the definition of stability is based on variability in the fitted estimates rather than on the appearance of stability in response rates or the number of sessions per condition. The advantage of defining stability by k and Re values rather than these other measures is simply that k and Re are the dependent measures of interest; therefore, it is sensible to define stability using these measures.

EXPERIMENT 1

Experiment 1 examined the effects of adding and removing an alternative source of reinforcement on the coefficients of the hyperbolic matching equation. Rats were initially trained on a series of VI schedules; then, as in Bradshaw's (1977) study, an alternative source of reinforcement (providing a fixed rate of reinforcement) was added to the context. Following this phase, the single-operant condition was reinstated. The purpose of the experiment was to test the interpretation of Re by manipulation of contextual sources of reinforcement.

METHOD

Subjects

Six male Wistar rats served as subjects. All subjects were experimentally naive. The subjects were maintained at 85% of free-feeding body weights.

Apparatus

The experiment was conducted in standard operant conditioning chambers (Med Associates, Model ENV-001: 28 cm by 29 cm by 22 cm) with two levers. The levers were situated 7 cm above the floor, separated by 8 cm, and operated by a force of approximately 0.30 N. Five centimeters above each lever was a stimulus light that signaled when the lever was operative. Below each lever was a circular opening, 2 cm in diameter, that allowed access to a 0.1-mL dipper of sucrose solution. The dipper sat in a trough and was raised into the recessed opening when a reinforcement requirement was met. The chamber was housed in a sound-attenuating, ventilated shell. Experimental events were controlled and recorded by a PC computer and Med Associates modular interface.

Procedure

In the single-operant condition, only the right lever was operative. An experimental session consisted of exposure to a series of seven VI schedules. The programmed interreinforcement intervals for these schedules approximated an exponential distribution (Fleshler & Hoffman, 1962), so that the conditional probability of reinforcement was constant. Each schedule was constructed by multiplying a list of interval values with a mean of 3 s by a multiplier. The schedules were presented in the following order: VI 90 s, VI 39 s, VI 12 s, VI 4.5 s, VI 6 s, VI 27 s, and VI 60 s. The stimulus light above each lever signaled when a schedule was in effect, and each component was separated by a 7.5-s blackout (no lights on).

Each component duration began with an initial period of brief exposure to the schedule in effect in that component. The durations of the initial periods for the seven components were 105 s, 60 s, 24 s, 18 s, 23 s, 55 s, and 80 s, respectively. Following the initial period, the terminal period commenced. Responses, time, and reinforcement recorded during the terminal periods were used in the calculation of response and reinforcement rates. Component durations were 800 s, 426 s, 238 s, 162 s, 180 s, 350 s, and 618 s, respectively. The durations of the components and initial periods were approximately proportionate to the reinforcement rates, with the constraint that a minimum of eight reinforcements were available per component.

The reinforcer was 3 s of access to an 11.5% sucrose solution. During the reinforcement period and for the immediately following 1.5 s, the interval timer and stimuli were inoperative. Feedback for a response was provided by shutting the stimulus light off for 0.025 s.

For the concurrent or choice phase, a VI schedule with a mean of 27 s was programmed
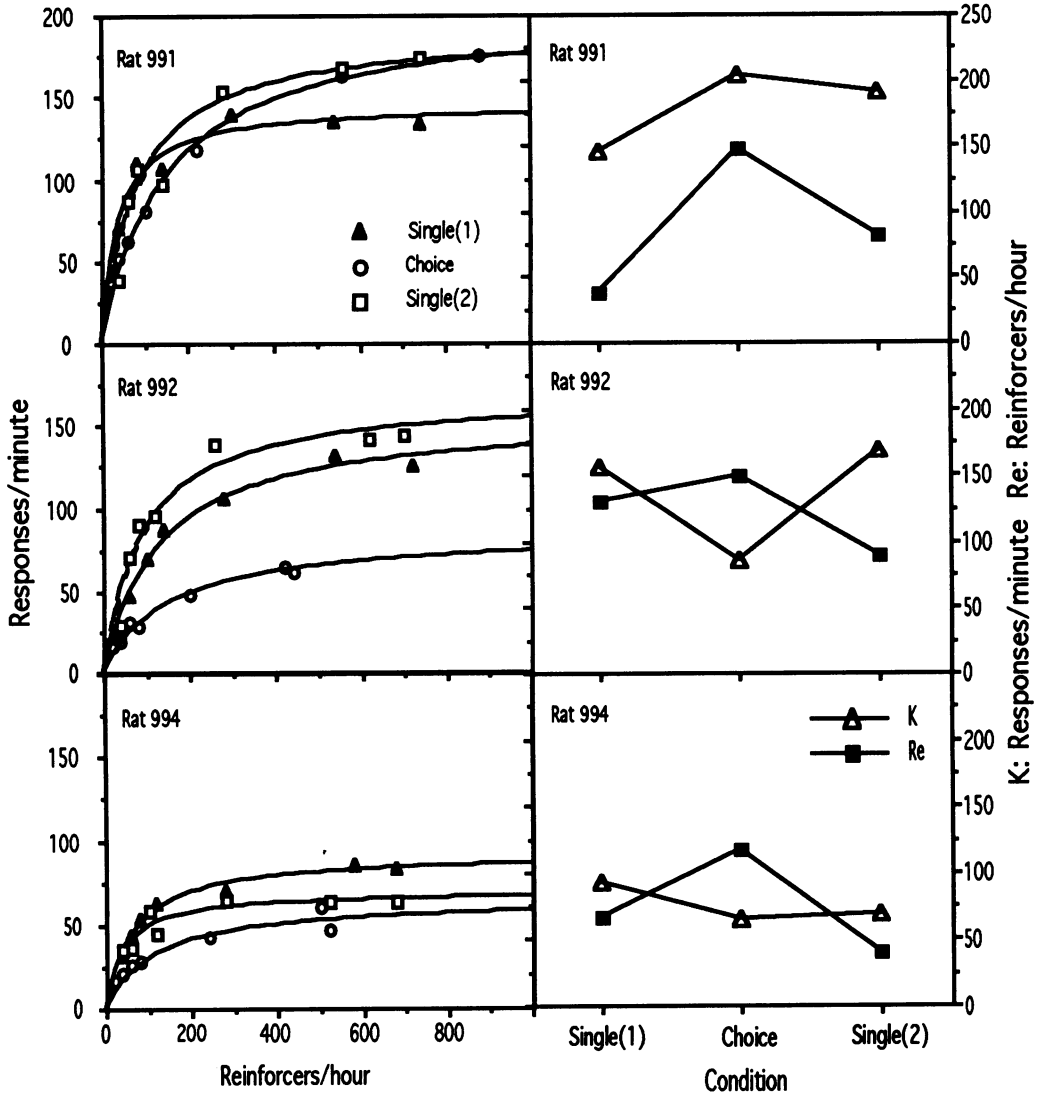
Fig. 1a.   Hyperbolic curves relating response and reinforcement rates (left graphs) and associated k and Re values (right graphs) for each subject in the two single-operant and choice conditions.

to operate independently on the left lever while the right alternative was in operation. The stimulus light above the left lever signaled when the schedule was in effect. A 2.5-s changeover delay (COD) with a two-response require-ment was programmed to prevent the adven-titious reinforcement of switching.

Reinforcement for the left alternative was also 3 s of access to an 11.5% sucrose solution delivered to the dipper cup opening below the left lever. The operation of the right alternative remained the same as in the single-operant condition. The final phase of the experiment involved a return to the single-operant con-dition.

A condition remained in effect until the fol-lowing criteria were met. First, a minimum of eight sessions had to elapse before performance could be judged stable. Second, the k and Re values over the last 5 consecutive days could be neither the highest nor the lowest for the condition. Finally, there could be no trend in the k and Re values over the last 3 days. Wil-kinson's (1961) method of estimating the pa-rameters of a hyperbolic function was used to generate k and Re values used for stability
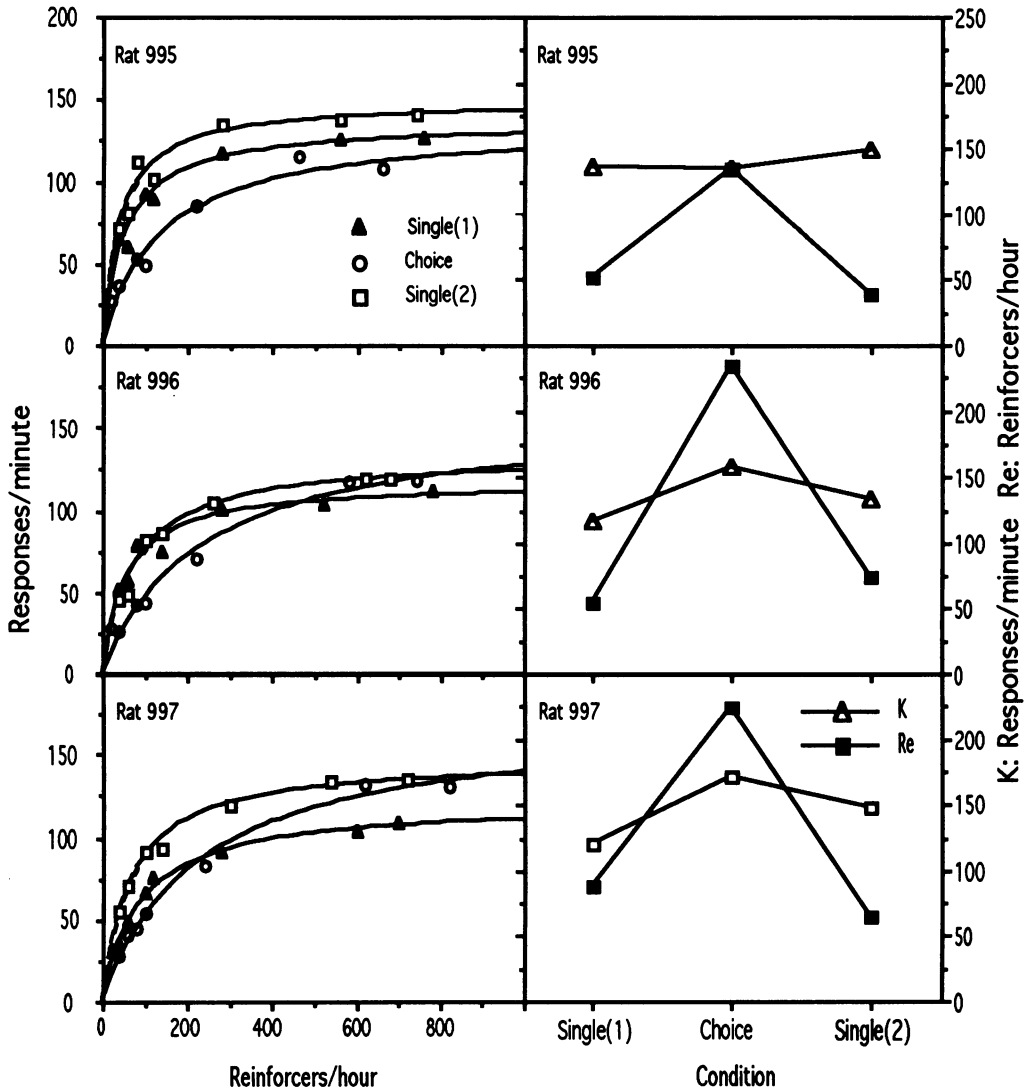
Fig. 1b. Hyperbolic curves relating response and reinforcement rates (left graphs) and associated k and Re values (right graphs) for each subject in the two single-operant and choice conditions.

judgments. The number of sessions to meet stability criteria for each subject in each condition are shown in Appendix A.

RESULTS

Figures 1a, 1b, and 1c present hyperbolic curves and associated k and Re values in the two single-operant conditions and the choice condition for each subject and the group. Across conditions, no systematic changes in k were observed. For the group, the values of k in the first single-operant, choice, and second single-operant conditions were 127, 138, and 143

responses per minute, respectively. A repeated measures analysis of variance performed on the k values across the three conditions revealed no significant differences, $F(2, 10) < 1$. Thus, the value of k remained relatively stable across the three conditions.

In contrast, systematic changes in Re were observed. For each subject, the value of Re increased with the addition of the alternative source of reinforcement. For the group, the value of Re increased from 66 reinforcers per hour in the first single-operant condition to 173 in the choice condition, and then decreased
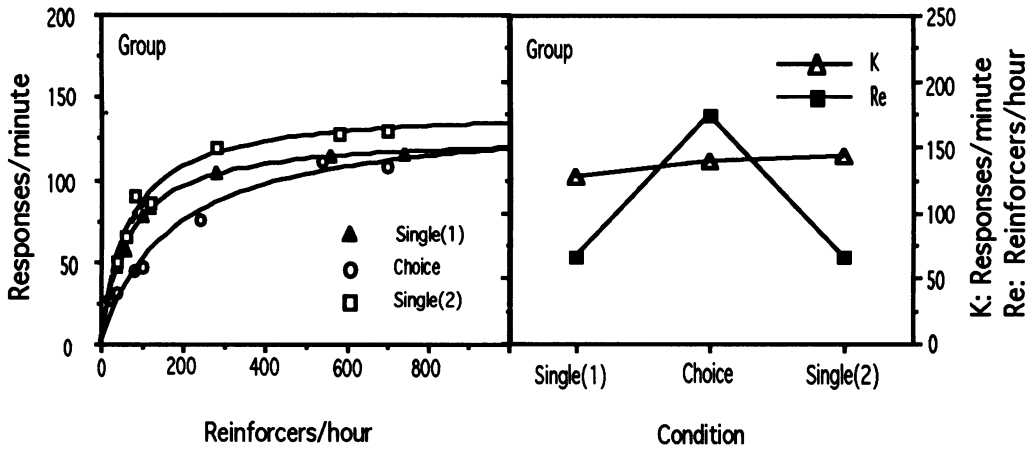
Fig. 1c. Hyperbolic curves relating response and reinforcement rates (left) and associated k and Re values (right) for the group in the two single-operant and choice conditions.

to 66 upon return to the single-operant condition. A repeated measures analysis of variance revealed that the change in Re with the addition of the single VI alternative was significant, $F(2, 10) = 18.49$, $p < .001$. The average increase in Re was 107 reinforcers per hour; this approximates the obtained rate of reinforcement on the VI 27-s schedule of 91 reinforcers per hour.

Response and reinforcement rates in the single-operant conditions and the choice condition in each component for each rat are shown in Appendix B. Of interest in this appendix are the data for the choice condition. Inspection of the absolute response and reinforcement rates for the variable and single VI alternatives show that there was negative covariance between rates. When the response rate on the variable alternative was high, the rate on the single VI

alternative was low. Conversely, when the response rate on the single VI alternative was high, the rate on the variable alternative was low. An equivalent relation occurred for obtained reinforcement rates. This covariance reflects a matching relation between the variable and single VI alternatives and occurs despite the constancy of the schedule of reinforcement on the single VI alternative. For example, for Rat 991, the obtained rate of reinforcement from the single VI alternative across the components ranged from 0 reinforcers per hour to 107 reinforcers per hour, even though the scheduled rate of reinforcement was always 133 reinforcers per hour. More important, because the rate of reinforcement from the single VI alternative was incorporated in the estimate of Re in the choice condition, the variance in reinforcement from this alternative has implications for the constancy of Re. The implications of this variance will be taken up in the discussion.

Table 1 shows the results of an analysis of the relationship between relative response and reinforcement rates on the two alternatives in the choice condition using the logarithmic form of the generalized matching law (Baum, 1974). The form of this equation is

$$\log(B_1/B_2) = a \log(R_1/R_2) + \log b. \quad (2)$$

In Equation 2, B_1 and B_2 represent responses on the two alternatives, and R_1 and R_2 represent reinforcements obtained on the respective alternatives. The parameters a and $\log b$

Table 1

Slope, intercept, and percentage of variance accounted for (VAC) from the regression of log response ratios on log reinforcement ratios. Standard errors of the estimates are given in parentheses.

Rat	Slope	Intercept	VAC
991	0.84 (0.03)	0.51 (0.02)	99
992	0.60 (0.06)	0.27 (0.02)	96
994	0.67 (0.09)	−0.04 (0.04)	92
995	0.85 (0.06)	0.29 (0.05)	98
996	0.92 (0.06)	0.19 (0.05)	98
997	0.87 (0.03)	0.16 (0.02)	100
Group	0.80 (0.03)	0.24 (0.02)	99

are the slope and intercept of a line fitted to the log response and log reinforcement ratios. Equation 2 can be used to assess how well data conform to the matching law. Normative matching is represented by a slope of 1.0 and an intercept of 0.0. Table 1 shows that slopes ranged from 0.60 to 0.92, and intercepts ranged from −0.04 to 0.51. Estimates of the percentage of variance accounted for ranged from 92% to 100%. From the group data, the slope was 0.80 and the intercept was 0.24, with 99% of the variance accounted for.

The slopes indicate that relative response rates undermatched relative reinforcement rates. Undermatching, in this context, suggests that response allocation to the varied alternative was less extreme than simple matching would predict. The intercepts show a bias or unaccounted-for systematic preference for the varied alternative.

DISCUSSION

In general, the results were qualitatively and quantitatively consistent with the Herrnstein (1970) interpretation. Qualitatively, the value of Re increased with the addition of the alternative source of reinforcement while k remained relatively constant. With the removal of the additional reinforcement source, Re decreased to its previous level. Quantitatively, the change in Re was approximately 18% greater than the obtained rate of reinforcement from the added source. Thus, the change in Re was a reasonably accurate reflection of the nominal change in background reinforcement.

In contrast to previous attempts, the value of Re neither markedly overestimated (Bradshaw, 1977) nor underestimated (White et al., 1986) the rate of reinforcement added to the context. Furthermore, the value of Re for the choice condition was never less than the obtained rate of reinforcement from the added alternative. In contrast, White et al. found that in two groups of rats, all but 1 subject (out of 16) showed a value of Re less than the obtained rate of reinforcement from the source of reinforcement added to the context.

White et al. (1986) explained this underestimation as a consequence of severe undermatching. In their study, the slopes for the groups receiving 68, 26, and 9 reinforcers per hour were 0.59, 0.48, and 0.39, respectively. In contrast, the level of undermatching observed in this present study was less than the

level observed by White et al. (1986). It is possible that the severity of undermatching was a function of the shorter COD used in their study. (The COD in the present study was 2.5 s compared to 1 s in their study.) Experiment 2 will further substantiate the effects of a change in sensitivity on estimates of k and Re.

Finally, there is the issue of variance in the rates of reinforcement from the single VI source (Rf) in the choice condition and the assumption of the constancy of Re. Stated briefly, Re is assumed to remain constant within a context and across components in the within-session procedure in both the single-operant and choice conditions. In the single-operant conditions, Re equals the rate of reinforcement from sources of reinforcement associated with behavior other than lever pressing (e.g., sniffing, grooming, and pacing). Collectively, the rate of reinforcement for these kinds of behavior will be referred to as Ro. In the choice condition, Re is a joint function of the rates of reinforcement from the single VI source of reinforcement (Rf) added to the context and the sources of reinforcement associated with behavior other than lever pressing (Ro). Thus, in the single-operant condition, $Re = Ro$, whereas in the choice condition, $Re = Rf + Ro$.

The problem that arises with variance in Rf in the choice condition is how can Re remain constant if Rf varies? If Ro remains constant, then any variance in Rf must produce variance in Re, thereby violating the assumption of the constancy of Re. However, if instead one assumes that Ro varies, then Re remains relatively constant if Ro and Rf negatively covary in much the same manner as the varied (Rv) and single VI (Rf) alternatives do.

Is there any evidence to decide between these alternative assumptions about Ro in the choice condition? First, if Ro is assumed to be constant and independent of Rf and Rv, then variance in Rf will produce variance in Re. This has the following implications. In components in which the rate of reinforcement from the varied alternative (Rv) was low, the rate of reinforcement obtained from the single VI alternative was higher. Conversely, when the rate of reinforcement from Rv was high, the rate of reinforcement from Rf was lower. Consequently, if Ro was constant, then Re would be larger in components in which Rv was low and smaller in those components in which Rv

Table 2

Obtained *k* and *Re* estimates for the choice condition along with *k* and *Re* values estimated from predicted response rates using the *Re* values estimated in the Single-Operant 1 and Single-Operant 2 conditions.

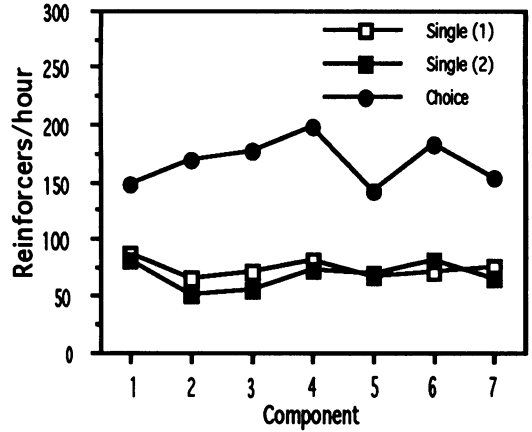|	Rat	Obtained choice	Choice predicted from Single-Operant 1	Choice predicted from Single-Operant 2
k values	991	203.29	236.05	234.72
	992	85.20	89.52	89.47
	994	64.81	72.76	72.79
	995	136.37	163.94	164.50
	996	157.89	188.84	188.47
	997	170.84	202.56	203.06
	Group	136.65	159.94	160.57
Re values	991	148.15	163.20	210.77
	992	149.33	229.55	188.01
	994	116.27	205.24	177.73
	995	135.21	188.15	174.45
	996	235.02	201.87	223.85
	997	224.19	240.29	214.04
	Group	169.30	198.67	203.33

Fig. 2.   Group average *Re* values by component in the two single-operant and choice conditions.

$$Bv = \frac{kRv}{Rv + Rf + Ro}. \qquad (3)$$

In equation 3, *Bv* represents the response rate predicted for the varied alternative, *k* is the asymptotic level of responding, *Rv* is the rate of reinforcement obtained from the varied alternative, *Rf* is the rate of reinforcement from the single VI alternative, and *Ro* is the estimated rate of reinforcement from other sources. For the choice condition, *Rf* and *Ro* comprise *Re*.

If the assumption that *Ro* is constant across conditions and components holds, then *k* and *Re* values estimated from the predicted response rates generated in this manner should concur with the *k* and *Re* values estimated for the obtained response rates in the choice condition. Table 2 shows the *k* and *Re* values obtained for the choice condition compared to the *k* and *Re* values estimated when the *Re* values from the first and second single-operant conditions are used to generate predicted response rates. A repeated measures analysis of variance showed that the *k* values from the predicted response rates were significantly greater than the obtained *k* values in the choice condition, $F(2, 10) = 18.43$, $p < .001$. For estimates of *Re*, the *Re* values for the predicted response rates were greater than the obtained *Re* values in the choice condition for 5 of the 6 rats, $F(2, 10) = 3.13$, $p < .10$. This analysis suggests that the assumption that *Ro* is invariant across conditions and components is not consistent with the process underlying the

was high. This particular pattern of variance in *Re* due to variance in *Rf* would result in higher than expected response rates in the components in which *Rv* was high and lower than expected response rates in components in which *Rv* was low. These differences in response rates should lead to inflated *k* and *Re* estimates in the choice condition compared to the single-operant conditions. However, the data show that the value of *k* across the choice and single-operant conditions remained relatively constant, and the change in the estimated value of *Re* accurately reflected the rate of reinforcement added to the context by the single VI alternative. Thus, the data do not show the inflation of the estimates of *k* and *Re* that would result from variance in *Re* due to variation in *Rf*, assuming a constant and independent *Ro*.

Second, the assumption that *Ro* is constant and independent of *Rf* and *Rv* can be further tested by using the *Ro* values estimated in the two single-operant conditions to estimate response rates for each component of the varied alternative in the choice condition. In the following equation, predicted response rates (*Bv*) were estimated for each component using the values of *Rv*, *Rf*, and *k* from the choice condition and the value of *Re* estimated from each single-operant condition:

generation of the response rates upon which k and Re values were estimated in the choice condition.

Finally, the assumption that Ro was constant across components in the choice condition can be tested by comparing the variance in the estimates of Re across components with the variance in Rf. Figure 2 shows the estimated values of Re for each component averaged across all individuals in the two single-operant conditions and the choice condition. Values of Re were estimated using the obtained response and reinforcement rates in each component. If Ro was constant and independent of Rf, then variance in the estimates of Re across components for the choice condition must be due to variance in Rf. If this is true, then the variance in Re should equal the variance in Rf. However, the variance in Re across components was only 422.81, compared to 1,334.17 for Rf. Thus, the variance in Re was less than would be expected if Ro was constant.

Together, this evidence suggests that Ro varied. Although the source of this variance is not certain, Ro probably covaried with Rf in much the same manner as Rf covaried with Rv. As such, variance in the obtained rates of reinforcement from a single VI alternative would not seriously violate the assumption of the constancy of the composite Re across components.

It should also be pointed out that the idea that Rf and Ro covary so that their sum (Re) remains approximately constant appears to violate the assumption that the ratio of choices between two alternatives is constant, irrespective of the number or nature of other alternatives (e.g., Luce, 1959). For example, according to the analyses presented in this paper, the ratio Bf/Bo must have decreased as the obtained rate of reinforcement on the right lever increased. However, violation of the "independence from irrelevant alternatives" rule is not unprecedented. For example, Prelec and Herrnstein (1978) found that preference between a ratio and an interval schedule varied as a function of the presence of a third (interval) schedule.

EXPERIMENT 2

Previous tests of the interpretation of Re have focused on the effects of changes in quality or magnitude of the foreground reinforcement. However, the efficacy of reinforcement for maintaining behavior varies not only with quality and magnitude but also with manner of presentation. For example, signaling reinforcement availability has been shown to decrease substantially the effectiveness of reinforcement for maintaining behavior. Thus, the unpredictability of reinforcement is another dimension that contributes to reinforcement efficacy, and Re should vary with changes in the predictability of reinforcement.

Previous research has shown that signaling reinforcement on one alternative in a concurrent procedure decreases responding to the signaled alternative. This decrease in responding on the signaled alternative results in a concomitant increase in the proportion of responses allocated to the unsignaled alternative in the absence of an increase in the rates of reinforcement on the unsignaled alternative (Bradshaw, Szabadi, Bevan, & Ruddle, 1979; Catania, 1963; Marcucella & Margolius, 1978; Wilkie, 1973).

Bradshaw, Szabadi, Bevan, and Ruddle (1979) exposed 3 adult female humans to five concurrent VI VI schedules. The schedules of reinforcement on one alternative varied while the schedule of reinforcement on the other alternative remained fixed. Signaling reinforcement availability on the varied alternative produced a marked decrease in responding to that alternative and a marked elevation of response rates to the single VI alternative. Hyperbolic curves fit to the response rates prior and subsequent to signaling reinforcement availability illustrated the marked decline in response rates on the reinforcement schedules on the varied alternative.

An analysis based on the generalized matching law of the relationship of response and time ratios to reinforcement ratios showed that signaling reinforcement on the varied alternative produced a marked increase in bias toward the unsignaled single VI alternative while the sensitivity parameter remained relatively unchanged. The marked shift in the bias parameter reflected the decrease in responding to the varied alternative. Time allocation showed the same pattern as response allocation.

Marcucella and Margolius (1978) also observed that signaling reinforcement on an alternative decreased responding on that alternative, resulting in a similar deviation from matching. However, the deviation from match-

ing was markedly greater for responses than for time allocation. In contrast to the results of Bradshaw, Szabadi, Bevan, and Ruddle (1979), no elevation of response rates on the unsignaled alternative was observed.

Wilkie (1973) exposed pigeons to concurrent VI VI schedules using a Findley (1958) procedure. Reinforcement availability on the signaled alternative was signaled by the illumination of the houselight. Results showed that when reinforcement availability was signaled, both responding and time allocation to the signaled schedule were decreased. As in the study of Marcucella and Margolius (1978), the decrease in responding was markedly greater than the decrease in time allocation.

These studies show that the basic effect of signaling reinforcement on one alternative in a concurrent schedule is a decrease in responding on the signaled alternative. This produces a concomitant change in relative behavior and time allocation that is markedly greater for behavior than for time. Although this effect has been studied using concurrent schedules of reinforcement, it has not been analyzed in terms of the parameters of the hyperbolic matching equation. Note that Bradshaw, Szabadi, Bevan, and Ruddle (1979) fit curves to response rates; however, no analysis in terms of fitted parameters was offered.

In the present study, two conditions were arranged. In the signaled reinforcement condition, the light over the left lever was programmed to flash on and off when reinforcement became available on that alternative. The light continued to flash until reinforcement was earned. Four rats were switched into this condition from the second single-operant condition in Experiment 1. A second condition was added, based on the observation that in the components with low rates of reinforcement on the unsignaled variable alternative (i.e., 40 and 45 reinforcers per hour), subjects switched to the signaled single VI alternative when the light began to flash, but in the components with the highest rates of reinforcement (i.e., 600 and 800 reinforcers per hour), some subjects remained on the unsignaled alternative even when the signal light was flashing. To increase the probability of the rats switching to the signaled alternative in the high-reinforcement-rate components, the subjects were placed in a signaled left reinforcement condition with no COD. The 2.5-s COD was re-

moved so that the only requirement to earn reinforcement on either alternative was to make two consecutive responses. The purpose of the experiment was to investigate the effect of signaling the availability of a contextual source of reinforcement on the value of Re estimated from a foreground source of reinforcement.

METHOD

Subjects and Apparatus

Subjects 991, 994, 996, and 997 were used in Experiment 2. The apparatus described in Experiment 1 was used in Experiment 2.

Procedure

The general procedure was the same as that used in Experiment 1. The first condition was the same as the choice condition in Experiment 1, with the exception that when reinforcement was set up on the single VI alternative, the left stimulus light flashed on and off until the reinforcer was earned. This was the signaled reinforcement condition. The second condition was also a signaled reinforcement condition, but with the 2.5-s COD removed.

RESULTS

Figures 3a and 3b present the hyperbolic curves and associated k and Re values for each subject and the group in the choice or unsignaled reinforcement condition in Experiment 1, the signaled reinforcement condition, and the signaled reinforcement with no COD condition. For the group, mean values of k were 150, 148, and 115 responses per minute, respectively. For Re, the mean values were 184, 147, and 105 reinforcers per hour, respectively. Signaling reinforcement on the single VI alternative decreased average Re by 37 reinforcers per hour, $F(1, 3) = 24.39$, $p < .05$, whereas the average value of k remained constant, $F(1, 3) < 1$. With the subsequent removal of the changeover delay, k declined by approximately 33 responses per minute, $F(1, 3) = 8.37$, $p < .10$, and Re dropped by approximately 42 reinforcers per hour, $F(1, 3) = 10.13$, $p < .05$.

Obtained reinforcement rates from the single VI alternative also changed when reinforcement was signaled. Three rats obtained more reinforcers from this alternative when reinforcement was signaled. For Rats 991, 994, 996, and 997, differences in obtained rein-
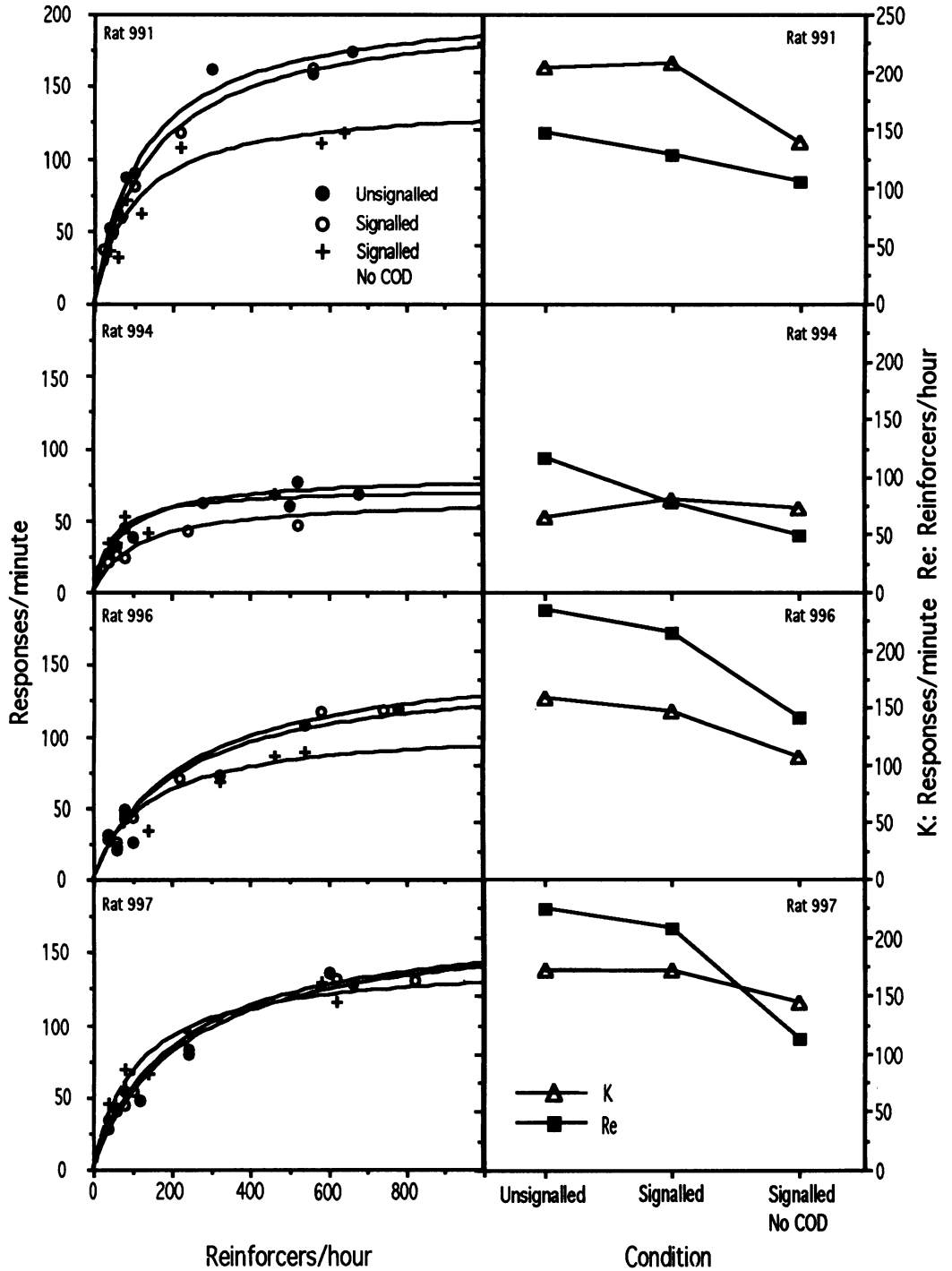
Fig. 3a. Hyperbolic curves relating response and reinforcement rates (left) and associated k and Re values (right) for each subject in the unsignaled reinforcement, signaled reinforcement, and signaled reinforcement with no COD conditions.
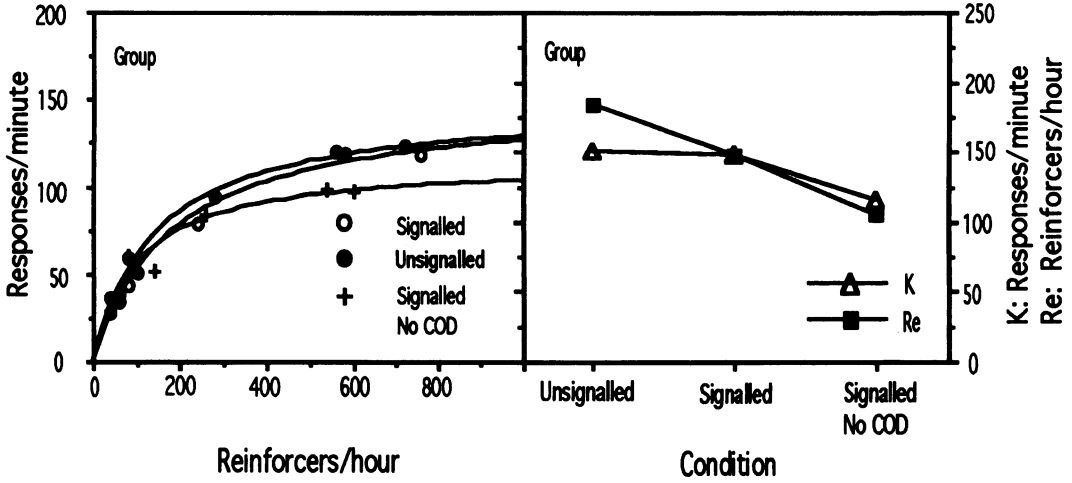
Fig. 3b. Hyperbolic curves relating response and reinforcement rates (left) and associated k and Re values (right) for the group in the unsignaled reinforcement, signaled reinforcement, and signaled reinforcement with no COD conditions.

forcement between the signaled and unsignaled conditions were 3.8, −12.2, 9.9, and 14.2 reinforcers per hour, respectively. Thus, on average, the obtained reinforcement rate on the single VI alternative was greater when reinforcement availability was signaled ($M = 98.2$) than when reinforcement was not signaled ($M = 94.1$), although the rate was not statistically significantly greater, $F(1, 3) < 1$.

Table 3 presents the results of an analysis of the relationship between relative response and reinforcement rates for the conditions of signaled reinforcement and signaled reinforce-

ment with no COD for each subject using Equation 2. Figure 4 depicts the linear regression of log response ratios on log reinforcement ratios for the 4 subjects that experienced the conditions of unsignaled reinforcement, signaled reinforcement, and signaled reinforcement with no COD. Comparison of the unsignaled and signaled conditions shows that the decline in Re observed in Figure 3b appears as an increase in bias. For the unsignaled condition, the slope and intercept were 0.80 and 0.22, respectively. In
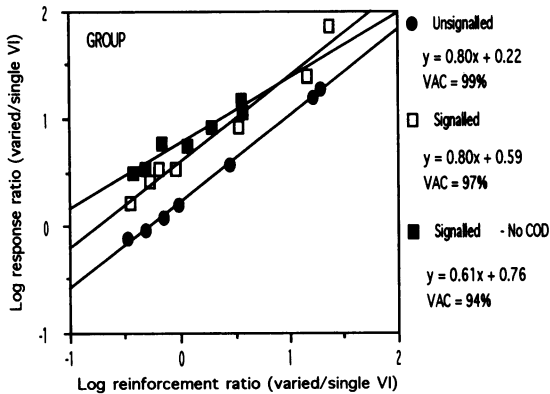
Fig. 4. Log ratio of responses as a function of the log ratio of obtained reinforcements for the unsignaled, signaled, and signaled with no COD conditions for the group. Values for the slope, intercept, and percentage of variance accounted for (VAC) best fitting straight lines are given.

Table 3

Slope, intercept, and percentage of variance accounted for (VAC) from the regression of log response ratios on log reinforcement ratios in the signaled reinforcement and signaled reinforcement with no COD conditions. Standard errors of the estimates are given in parentheses.

Rat	Slope	Intercept	VAC
Signaled reinforcement			
991	0.83 (0.07)	0.82 (0.06)	97
994	0.67 (0.11)	0.42 (0.07)	88
996	0.90 (0.09)	0.42 (0.08)	95
997	0.87 (0.14)	0.64 (0.09)	90
Group	0.80 (0.06)	0.59 (0.05)	97
Signaled reinforcement with no COD			
991	0.44 (0.14)	1.10 (0.05)	67
994	0.56 (0.15)	0.57 (0.05)	74
996	0.56 (0.12)	0.62 (0.05)	82
997	0.73 (0.04)	0.85 (0.02)	98
Group	0.61 (0.07)	0.76 (0.03)	94

comparison, the slope and intercept in the signaled condition were 0.80 and 0.59, respectively. Thus, signaling reinforcement on the single VI alternative produced a concomitant increase in proportionate response allocation to the varied alternative; this is reflected in a 0.37 increase in the intercept or bias parameter while the slope remained unchanged.

Elimination of the COD produced greater undermatching and bias. For the group, the slope decreased from 0.80 to 0.61, and the intercept increased from 0.59 to 0.76. The decrease in the slope suggests that the subjects' behavior became less sensitive to differences in relative rates of reinforcement. The level of undermatching observed in this condition approximated that observed by White et al. (1986). In addition, the increase in the intercept reflected a further change in proportionate behavior and time allocation to the varied alternative.

Table 4 shows that signaling reinforcement produced little change in the rate of changeovers; however, removing the COD produced a marked increase in the rate of changeovers. This increase in changeovers was associated with both a decline in the sensitivity parameter and a decline in k for every rat. In general, this result is consistent with a view that changes in k are a function of a change in the topography of responding (Porter & Villanueva, 1988).

DISCUSSION

Signaling reinforcement on the single VI alternative decreased responding on that alternative. This change in responding was reflected by a decrease in Re in the hyperbolic matching equation analysis and by an increase in bias in the generalized matching law analysis. Signaling the availability of reinforcement removed the unpredictability of reinforcement on the single VI alternative and, as a consequence, decreased the efficacy of this source of reinforcement to maintain lever pressing.

When reinforcement on the single VI alternative remained variable, but not unpredictable, the value of Re no longer reflected the rate of reinforcement obtained from the single VI alternative. In fact, the changes in Re and obtained reinforcement rate were in opposite directions. This result demonstrates that the capacity of a source of reinforcement

Table 4

Average changeovers by component in each condition for each subject.

	Component by schedule (s)						
Rat	VI 90	VI 39	VI 12	VI 4.5	VI 6	VI 27	VI 60
Unsignaled condition							
991	79.0	39.8	10.0	0.4	2.0	31.4	68.0
994	65.0	40.2	14.0	7.6	8.6	33.0	62.8
996	87.6	51.8	19.4	1.4	0.8	37.0	69.8
997	86.0	48.6	16.8	1.2	0.0	36.2	71.8
M	79.4	45.1	15.0	2.7	2.9	34.4	68.1
Signaled condition							
991	76.4	34.4	3.6	0.4	0.0	21.8	45.2
994	80.0	39.4	11.6	4.8	1.6	27.2	49.6
996	77.0	40.2	14.4	0.8	1.2	29.0	51.8
997	93.4	50.4	19.6	5.0	2.8	31.0	70.6
M	81.7	41.1	12.3	2.8	1.4	27.3	54.3
Signaled no-COD condition							
991	75.4	31.0	16.0	9.6	9.6	22.4	44.8
994	101.2	51.4	20.8	12.2	12.2	33.4	54.4
996	116.8	56.4	28.2	12.6	14.8	34.2	63.4
997	109.0	55.8	23.4	8.4	7.0	38.6	76.2
M	100.6	48.7	22.1	10.7	10.9	32.2	59.7

to maintain behavior depends on more than simply the nominal rate of reinforcement from that source.

Subsequent removal of the COD substantially reduced k and produced a further decline in Re. In general, these changes were associated with an increase in the rate of changeovers and an increase in the severity of undermatching. This result is consistent with the observation by White et al. (1986) that severe undermatching and bias affect the estimation of k and Re values.

GENERAL DISCUSSION

In previous experiments, the introduction of a second experimenter-controlled reinforcement source increased Re. However, the nominal increase in reinforcement rate failed to predict the amount of change in Re. In contrast, in Experiment 1, the nominal increase in background reinforcement approximated the increase in Re. Thus, in Experiment 1, there was quantitative as well as qualitative agreement with the view that Re measures background reinforcement (Herrnstein, 1970, 1974).

The following procedural differences may account for the different finding. First, subjects

in previous studies were exposed to a single VI or concurrent VI schedule in each condition, and the matching equation was fit to the response and reinforcement rates obtained across conditions. In the present study, subjects experienced a series of VI schedules in each session, and the equation was fit to the rates generated in each session. This within-session procedure is less susceptible to confounding effects associated with the passage of time. Second, in previous studies, stability was defined by inspection of response rates or a prespecified number of sessions. In the present study, stability was defined by the fitted parameters, k and Re. Finally, with respect to the study by White et al. (1986), the present study used a longer COD.

One potential criticism of this procedure is that the changes in response rates within the session reflect a within-session pattern of responding (McSweeney & Hinson, 1992) rather than changes in reinforcement rates. However, this procedure has been used in numerous studies in a variety of contexts with an ascending order of VI schedules (Heyman, 1983; Petry & Heyman, 1994), a descending order (Heyman, 1983), a random order (Heyman et al., 1986; Heyman & Monaghan, 1987), and an ascending and then descending order (Heyman, 1992). In each case, response rates have varied in accord with the obtained rates of reinforcement in an orderly manner. Therefore, it is unlikely that the orderliness of the data is a function of the within-session changes in response rates, as suggested by McSweeney and Hinson (1992), rather than the VI values manipulated within the session.

In Experiment 2, the effect of signaling reinforcement availability on one alternative produced the expected decrease in responding to that alternative. This change was associated with a decline in the value of Re and an increase in bias toward the unsignaled alternative in the generalized matching law analysis. The decline in Re occurred despite an increase in the rate of reinforcement obtained from the left alternative. In this context, Re no longer reflected the nominal rate of reinforcement. The implication is that predictability of reinforcement, reinforcement magnitude, reinforcement quality, reinforcement rate, and deprivation are all variables that alter the efficacy of reinforcement for maintaining behavior.

Finally, and perhaps, most important, there is the issue of variance in the sources of reinforcement that comprise Re. It is usually assumed that Re remains relatively constant; however, this constraint does not specify the relations among the sources of reinforcement that comprise Re. The simplest assumption is that each source remains constant across the components of the multiple schedule. However, this assumption brings with it certain implications that are not substantiated by the data. Instead, the alternative assumption, that Ro interacts and covaries with other extraneous sources, appears to be more consistent with the processes underlying the generation of the data.

As originally conceived, the value of adding extraneous sources of reinforcement to the context is not only as a test of the accuracy of the hyperbolic matching equation. In addition, the value of this procedure comes from the challenge provided to our assumptions about the nature of uncontrolled sources of reinforcement that compete with those arranged by the experimenters.

REFERENCES

Baum, W. M. (1974). On two types of deviation from the matching law: Bias and undermatching. *Journal of the Experimental Analysis of Behavior, 22,* 231–242.

Bradshaw, C. M. (1977). Suppression of response rates in variable-interval schedules by a concurrent schedule of reinforcement. *British Journal of Psychology, 68,* 473–480.

Bradshaw, C. M., Szabadi, E., & Bevan, P. (1976). Behavior of humans in variable-interval schedules of reinforcement. *Journal of the Experimental Analysis of Behavior, 26,* 135–141.

Bradshaw, C. M., Szabadi, E., & Bevan, P. (1979). The effect of punishment on free-operant behavior in humans. *Journal of the Experimental Analysis of Behavior, 31,* 71–81.

Bradshaw, C. M., Szabadi, E., Bevan, P., & Ruddle, H. V. (1979). The effect of signaled reinforcement availability on concurrent performances in humans. *Journal of the Experimental Analysis of Behavior, 32,* 65–74.

Catania, A. C. (1963). Concurrent performances: Reinforcement interaction and response independence. *Journal of the Experimental Analysis of Behavior, 6,* 253–263.

de Villiers, P. A., & Herrnstein, R. J. (1976). Toward a law of response strength. *Psychological Bulletin, 83,* 1131–1153.

Findley, J. D. (1958). Preference and switching under concurrent scheduling. *Journal of the Experimental Analysis of Behavior, 1,* 123–144.

Fleshler, M., & Hoffman, H. S. (1962). A progression for generating variable-interval schedules. *Journal of the Experimental Analysis of Behavior, 5,* 529–530.

Hamilton, A., Stellar, J. R., & Hart, E. B. (1985). Reward, performance, and response strength method in self-stimulating rats: Validation and neuroleptics. *Physiology and Behavior, 35,* 897–904.

Herrnstein, R. J. (1970). On the law of effect. *Journal of the Experimental Analysis of Behavior, 13,* 243–266.

Herrnstein, R. J. (1974). Formal properties of the matching law. *Journal of the Experimental Analysis of Behavior, 21,* 159–164.

Heyman, G. M. (1983). A parametric evaluation of the matching law. *Journal of the Experimental Analysis of Behavior, 40,* 113–122.

Heyman, G. M. (1992). The effects of methylphenidate on response rate and measures of motor performance and reinforcement efficacy. *Psychopharmacology, 109,* 145–152.

Heyman, G. M., Kinzie, D. L., & Seiden, L. S. (1986). Chlorpromazine and pimozide alter reinforcement efficacy and motor performance. *Psychopharmacology, 88,* 346–353.

Heyman, G. M., & Monaghan, M. M. (1987). Effects of changes in response requirement and deprivation on the parameters of the matching law equation: New data and review. *Journal of Experimental Psychology: Animal Behavior Processes, 13,* 384–394.

Luce, R. D. (1959). *Individual choice behavior: A theoretical analysis.* New York: Wiley.

Marcucella, H., & Margolius, G. (1978). Time allocation in concurrent schedules: The effect of signalled reinforcement. *Journal of the Experimental Analysis of Behavior, 29,* 419–430.

McSweeney, F. K. (1978). Prediction of concurrent keypeck and treadle-press responding from simple schedule performance. *Animal Learning & Behavior, 6,* 444–450.

McSweeney, F. K., & Hinson, J. M. (1992). Patterns of responding within sessions. *Journal of the Experimental Analysis of Behavior, 58,* 19–36.

Petry, N. M., & Heyman, G. M. (1994). Effects of qualitatively different reinforcers on the parameters of the response-strength equation. *Journal of the Experimental Analysis of Behavior, 61,* 97–106.

Porter, J. H., & Villanueva, H. F. (1988). Assessment of pimozide's motor and hedonic effects of operant behavior in rats. *Pharmacology Biochemistry and Behavior, 31,* 779–786.

Prelec, D., & Herrnstein, R. J. (1978). Feedback functions for reinforcement: A paradigmatic experiment. *Animal Learning & Behavior, 6,* 181–186.

White, K. G., McLean, A. P., & Aldiss, M. F. (1986). The context for reinforcement: Modulation of the response–reinforcer relation by concurrently available extraneous reinforcement. *Animal Learning & Behavior, 14,* 398–404.

Wilkie, D. M. (1973). Signalled reinforcement in multiple and concurrent schedules. *Journal of the Experimental Analysis of Behavior, 20,* 29–36.

Wilkinson, G. N. (1961). Statistical estimation in enzyme kinetics. *Biochemical Journal, 80,* 324–332.

APPENDIX A

Number of sessions to meet stability criteria for each subject in each condition.

Rat	Single 1	Choice	Single 2	Signal	Signal no COD
991	23	16	22	15	30
992	21	39	15	—	—
994	20	25	10	15	10
995	11	48	21	—	—
996	12	28	12	24	18
997	18	18	16	22	10

APPENDIX B

Absolute response rates (responses per minute) and absolute reinforcement rates (reinforcers per hour) for each component in the multiple schedule for each subject in the single-operant and choice conditions.

Rat	Com-po-nent	Single-Operant 1		Single-Operant 2		Choice			
		Absolute response rate	Absolute reinforce-ment rate	Absolute response rate	Absolute reinforce-ment rate	Absolute response rates		Absolute reinforcement rates	
						Varied	Single VI	Varied	Single VI
991	1	70.43	35.75	60.91	38.75	37.43	34.70	31.82	101.41
	2	109.55	84.48	106.91	92.85	62.06	27.27	61.91	92.38
	3	138.39	295.19	153.01	288.29	118.05	9.63	229.75	58.43
	4	134.13	749.47	173.91	734.31	175.04	1.11	874.42	0.00
	5	134.49	545.85	168.24	568.11	162.74	2.59	567.52	16.33
	6	106.56	134.70	97.30	132.45	80.41	23.75	99.45	99.45
	7	87.54	64.32	87.39	53.66	51.86	30.60	46.87	106.99
992	1	23.37	38.70	29.47	36.73	15.38	17.60	32.79	94.60
	2	68.96	98.97	90.53	88.27	30.79	18.61	77.90	105.18
	3	105.24	283.70	138.87	267.25	48.05	15.54	200.53	83.53
	4	124.96	719.16	144.33	702.32	61.65	10.84	430.77	67.47
	5	131.25	537.99	141.62	618.86	64.75	8.62	412.12	69.57
	6	87.05	138.13	95.29	110.57	27.81	13.93	81.61	62.07
	7	46.56	52.24	70.32	61.61	18.63	15.78	37.82	90.81
994	1	31.50	37.79	34.88	39.71	16.38	31.07	35.73	127.27
	2	53.23	82.92	57.62	92.80	25.64	37.21	69.83	120.58
	3	69.02	277.36	63.77	283.10	42.07	18.91	234.78	79.85
	4	83.33	670.32	63.45	670.32	46.97	11.78	521.10	83.44
	5	85.22	570.10	63.16	515.73	59.95	11.99	500.81	46.56
	6	61.85	110.34	44.58	112.85	23.79	44.76	86.64	107.32
	7	43.31	62.96	36.10	58.90	20.65	49.58	45.56	106.99
995	1	65.68	39.76	71.34	41.77	36.75	41.06	37.70	120.07
	2	92.54	98.82	111.91	70.05	57.52	30.62	81.99	96.61
	3	117.33	282.54	134.44	283.10	84.82	13.52	229.50	41.36
	4	126.24	754.29	141.05	732.63	107.34	2.34	654.55	13.56
	5	125.70	557.45	137.88	558.50	114.92	1.21	469.84	8.08
	6	88.95	126.92	101.91	118.27	49.18	26.75	109.98	94.28
	7	59.78	48.36	80.53	52.28	27.09	31.16	37.82	92.26
996	1	52.33	41.74	45.76	40.72	28.23	46.45	33.77	111.81
	2	78.51	86.33	82.08	94.74	42.95	39.81	81.99	107.35
	3	100.97	283.39	104.95	266.18	70.06	21.36	219.82	69.01
	4	111.65	788.81	119.05	685.47	118.28	1.65	748.39	8.99
	5	104.12	515.73	119.25	623.10	117.24	0.94	579.31	8.08
	6	75.08	134.87	85.86	137.62	44.01	29.42	104.68	102.06
	7	57.40	54.96	48.79	48.24	25.80	36.50	42.97	113.02
997	1	35.05	39.75	54.86	39.69	28.25	49.07	34.75	111.81
	2	66.48	103.09	91.37	94.49	44.84	46.26	75.87	103.02
	3	90.77	272.70	119.37	294.03	82.70	22.51	234.78	69.01
	4	108.65	702.32	135.19	717.47	130.49	1.57	817.98	8.99
	5	103.18	593.41	133.83	546.91	131.68	0.00	615.93	0.00
	6	75.52	123.77	93.75	134.70	54.13	32.38	109.98	99.45
	7	49.15	65.56	70.71	56.12	40.04	45.28	68.28	122.22

APPENDIX C

Absolute response and reinforcement rates for each component in the multiple schedule for each subject in the signaled left reinforcement and signaled left reinforcement with no COD conditions.

Rat	Com-po-nent	Signaled left reinforcement				Signaled left reinforcement with no COD			
		Absolute response rates		Absolute reinforcement rates		Absolute response rates		Absolute reinforcement rates	
		Varied	Single VI	Varied	Single VI	Varied	Single VI	Varied	Single VI
991	1	51.99	17.12	34.75	96.86	35.77	5.86	42.66	106.00
	2	87.42	15.55	92.38	129.62	71.77	4.92	71.83	113.92
	3	161.65	2.69	305.05	21.75	107.92	4.87	219.82	142.57
	4	174.28	0.37	654.55	4.47	118.13	3.92	640.00	100.00
	5	158.86	0.00	567.52	0.00	110.92	3.64	579.31	109.09
	6	89.72	11.66	104.68	112.65	62.60	4.25	126.23	118.03
	7	61.30	11.94	65.55	119.13	32.57	4.94	57.44	128.45
994	1	27.00	16.66	37.70	112.98	34.70	14.45	41.66	116.51
	2	44.89	16.48	67.84	116.13	53.32	14.98	88.19	122.83
	3	61.97	8.14	276.92	72.59	62.08	7.34	282.43	110.13
	4	68.87	6.90	684.54	57.14	61.33	8.71	509.09	141.18
	5	76.94	1.84	511.48	16.33	68.04	5.71	469.84	114.29
	6	37.87	16.42	109.98	99.45	41.46	15.42	140.23	115.33
	7	31.64	15.80	50.80	98.09	33.69	15.24	69.66	131.60
996	1	30.68	42.58	37.70	122.46	27.45	17.35	28.91	130.91
	2	48.56	25.61	67.84	116.13	45.52	12.14	75.87	129.62
	3	72.95	14.54	310.85	87.23	68.64	13.54	328.63	114.07
	4	118.83	0.75	782.42	8.99	89.60	5.93	545.79	88.89
	5	107.45	1.08	544.54	12.18	86.24	5.87	469.84	114.29
	6	26.25	18.69	91.72	131.78	34.14	8.14	145.95	104.68
	7	20.56	23.51	45.56	113.02	23.26	9.46	48.17	125.32
997	1	34.03	18.70	34.75	114.16	45.38	13.59	43.66	108.32
	2	54.18	16.27	67.84	120.58	69.15	11.84	88.19	134.21
	3	79.63	11.64	239.87	83.53	95.42	8.15	239.87	110.13
	4	128.98	3.26	669.39	37.21	116.57	3.58	625.74	78.05
	5	135.77	1.11	591.30	29.02	129.54	2.72	579.31	60.22
	6	47.84	13.54	118.03	126.23	65.93	8.11	134.58	109.98
	7	41.63	13.53	65.55	109.99	42.86	12.27	46.87	116.06