

Instrumental responding by rats on free-operant schedules with components that schedule response-dependent reinforcer omission: Implications for optimization theories

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In two experiments, we assessed whether rats optimize the number of reinforcers per response. In Experiment 1, one group of rats was trained to leverpress for food reinforcement on a simple variable-interval (VI) 60-sec schedule. For another group, a negative fixed-ratio component was imposed on the VI schedule to produce a conjoint contingency in which reinforcement became available on the VI schedule but was omitted when the ratio criterion was satisfied. In Experiment 2, one group of rats responded on a VI schedule and also received response-independent food. For another group, responding above a certain rate canceled the response-independent food. Despite the negative contingency experienced by the groups in Experiments 1 and 2, responding was maintained at a level at which the number of obtained reinforcers was reduced substantially below the maximum number possible. In addition, in both experiments, the groups that experienced the negative contingency responded at a lower rate than did a yoked control group that experienced the same frequency of reinforcement but lacked the negative component. These results demonstrate that although rats do not optimize their behavior with respect to reinforcement, they are nevertheless sensitive to some aspect of the instrumental contingency in operation.

There are a number of molar-optimization theories of instrumental performance, for example, optimal foraging theories (Houston & McNamara, 1985; Lea, 1981), the value-maximizing model (Rachlin & Burkhard, 1978), minimal distance models (Staddon, 1979), conservation theory (Allison, 1981), and response-deprivation accounts (Timberlake, 1980). However, these models contain many common assumptions and it is possible to describe three broad classes of such theories on the basis of their similarities.

Some optimization theories share the principles of optimal foraging theory (see Collier, Hirsch, & Kanarek, 1977; Houston & McNamara, in press; Krebs & McCreery, 1984; Lea, 1981, for reviews). Optimal foraging theory claims that the laws of learning and performance operate to ensure optimal behavior, that is, behavior that maximizes energy gain per unit of time spent foraging (Lea, 1981). However, the strategy or process by which this

optimal outcome is achieved is the subject of some debate (see Krebs, Kacelnik, & Taylor, 1978; Lea & Dow, 1987).

Maximization theories (e.g., Baum, 1981; Rachlin, 1978; Rachlin, Battalio, Kagel, & Green, 1981) contain three basic assumptions: (1) constraints on behavior exist so that only a limited number of actions can be performed at once, (2) any such action has a determinable value, usually measured in terms of preference for engaging in that activity, and (3) organisms act to maximize the value of a given situation. The level of instrumental performance is the result of a resolution of the conflict between the value of engaging in the measured operant behavior and the value to be gained from engaging in other behaviors that may compete with that response (cf. Rachlin, Green, Kagel, & Battalio, 1976). In common with economic theories (see Hursh, 1984, for a review), maximization theories assume that leisure time (time spent not responding) is highly substitutable for reinforcement (see Burkhard, 1982; Rachlin & Burkhard, 1978). That is, reinforcement and leisure time will be readily engaged in (Burkhard, 1982). The point of maximum value is the point at which the maximum reinforcement and the maximum leisure time (within the schedule constraints) are achieved. Hence, common to both maximization and optimal foraging theories is the notion that animals will at-

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tempt to maximize gain (e.g., energy intake, reinforcement, leisure time, utility) and minimize costs (e.g., energy expenditure, response effort).

A third class of optimization account, behavioral regulation or equilibrium theories (Allison, 1981; Staddon, 1979; Timberlake, 1980, 1984; Timberlake & Allison, 1974), suggests that all behavior has a naturally occurring level of emission (set point). The set point is usually determined by measuring the level of unconstrained emission of the response in question. Staddon (1979) defined this set point as the level of performance at which every response is reinforced (i.e., a continuous reinforcement, or CRF, schedule). The level of instrumental performance seen under a particular schedule represents the animal's closest approximation, within the constraints of that schedule, to the behavioral set point (Allison, 1981; Timberlake, 1980; Timberlake & Allison, 1974). Strictly speaking, equilibrium theories do not predict absolute optimization (cf. Timberlake, 1984). However, in common with optimal foraging and maximization theories, equilibrium theories predict that, in most circumstances, behavior will move in the direction that might be considered optimal, that is, fewest responses (ideally, just one) for each reinforcement. The behavioral set point in equilibrium theory and the value of a particular activity in maximization theory are determined by the subject's preference for engaging in an activity relative to other activities in the absence of schedule constraint (see Allison, 1981; Rachlin & Burkhard, 1978). Moreover, this point is taken to be a determinant of the level of schedule-constrained activity. Thus, it is not clear that, leaving aside the degree of specificity, the two types of theories make different predictions. Both equilibrium theories and maximization theories suggest that behavior should approach a point of maximum value, or a behavioral set point; maximization theory claims that this point should be reached and equilibrium theory claims that this point should be approached.

Optimization theories have been developed to account for existing data (Rachlin & Burkhard, 1978; Staddon, 1979) and have only infrequently been subjected to testing. Recently, however, several researchers have attempted to assess the success of optimization theories in accounting for responding in novel free-operant situations (Ettinger, Reid, & Staddon, 1987; Mazur, 1981; Thomas, 1981; Tierny, Smith, & Gannon, 1987; Vaughan & Miller, 1984). The studies by Vaughan and Miller (1984; see also Vaughan, 1982) and Thomas (1981, 1983) differed from the others in that they employed schedules that contained a component that organized a negative contingency between responding and reinforcement. Under these conditions, Vaughan and Miller (1984) and Thomas (1981) found that subjects increase their rate of responding despite this performance resulting in a decreased rate of reinforcement. This result is at odds with an optimization analysis of instrumental performance, which would suggest that subjects should lower their rate of responding to obtain a greater number of reinforcers.

In terms of optimal foraging theory, animals in the negative-component schedule experiments of Vaughan and Miller (1984) and Thomas (1981) expended more effort (more responses) for fewer reinforcements than they would have obtained with less responding. Maximization theory assumes that much leisure time and much food should be preferred over all other combinations of these two commodities—especially over little reinforcement and little leisure, which is presumably the situation that occurred in the above experiments. Equilibrium theories would predict a fall in response rate in the negative-component schedule, and would not predict the maintained level of performance noted in the Vaughan and Miller study, or the rise in performance noted in the Thomas experiment.

However, there are difficulties in presenting these two experiments as evidence against optimization accounts. In neither the study by Vaughan and Miller (1984) nor the one by Thomas (1981) was it demonstrated that the animals were sensitive to the operative contingency. Staddon and Hinson (1983) criticized the failure of Mazur (1981) to find optimal performance in a choice situation on these grounds. Given that optimization theories assume sensitivity of the subject to the molar-feedback function (Ettinger et al., 1987), if the subjects were not sensitive to the contingency in operation, then the appropriate instrumental performance (i.e., optimal levels of responding) could not be expected to develop.

In the present experiments, we sought confirmation that animals are sensitive to some aspect of a negative contingency and, furthermore, we attempted to assess whether, despite sensitivity to the negative component of the schedule, animals' performance is still far from optimal. Such a finding would pose substantial problems for the most basic assumption common to many optimization theories.

EXPERIMENT 1

The first step in analyzing the success of optimization theories in predicting the results of negative-component schedules is to replicate the effect of a negative-component schedule. Vaughan and Miller (1984) arranged for reinforcement to be delivered according to a linear variable-interval (VI) schedule. A linear VI schedule is a contingency in which the timer continues to run when a reinforcement is set up, and in which uncollected reinforcers are stored in a bank. Vaughan and Miller also programmed a negative fixed-ratio (FR) component conjointly with the linear VI schedule, such that for every 30 responses emitted, a reinforcer was subtracted from the bank. Thus, if responding passed a certain level, reinforcements would be lost. Vaughan and Miller concluded that the response rates generated by the pigeons in their study gave no indication that the subjects were sensitive to the negative contingencies employed. Unfortunately, Vaughan and Miller did not include a comparison of the levels of responding generated by the subjects with a negative component imposed on the VI schedule with that of

a group given a simple VI schedule with a comparable reinforcement rate. The results from such a control condition were reported by Vaughan (1982; see also Ettinger et al., 1987, Experiment 2). In that study, higher rates were obtained with pigeons on a simple VI schedule than on a VI schedule with a negative component. However, this result was obtained using a within-subject design, and may reflect the length of training that the subjects had experienced rather than sensitivity to the contingency. In all cases, the simple VI schedule was experienced after the VI schedule with the negative component. Because Vaughan's subjects had more experience in responding per se at the time they received the VI schedule, this in itself could have promoted higher levels of responding on the matched VI schedule relative to the conjoint VI-FR schedule. Furthermore, since only data from the last five sessions were presented by Vaughan and Miller (1984), it is difficult to validate their claim that the birds on the negative-component schedule maintained responding. Response rates may have decreased over the course of training to the levels observed in the last five sessions.

To allow an assessment of the sensitivity to the negative component in the present study, we included a group that responded on a VI schedule that was yoked with respect to reinforcement frequency to the schedule with the negative component. It is not necessary that animals optimize in order to provide evidence that they are sensitive to the contingency. Behavior may be affected by the negative component without producing optimization. For example, sensitivity to the negative component could be manifested in a lower response rate in animals exposed to this treatment, relative to a yoked condition, but in which rates of responding in the former condition could be maintained at levels that substantially reduce the rate of reinforcement.

Method

Subjects. Twenty-four male hooded Lister rats served as subjects. The rats were 4–6 months old at the start of the study, had an ad-lib weight range of 275–360 g, and were maintained at 80% of this weight. The animals were housed in pairs, with water constantly available in the home cage. All subjects had previously served in a classical conditioning experiment in which they were exposed to food pellets, a houselight, and a tone. They were, however, naive with respect to leverpressing for food pellets.

Apparatus. Four identical operant chambers (Campden Instruments) were employed. Each chamber was housed inside a light- and sound-attenuating enclosure. A background masking noise [65 dB (A) relative sound-pressure level] was supplied by a ventilating fan. Each chamber was equipped with two retractable levers, one of which was withdrawn throughout the study. Centrally located between the two levers was a food tray into which reinforcement—one 45-mg food pellet—could be delivered.

Procedure. The animals needed no magazine training because of their previous experience. The subjects were trained to leverpress by reinforcing every response (a CRF schedule). Two sessions of CRF training were given, each terminated after 75 reinforcements had been earned. After this training, the animals were exposed to two 40-min sessions of a VI 30-sec schedule (range 2–90 sec). The subjects were subsequently trained on a linear VI 60-sec schedule (range 3–180 sec) for 12 40-min sessions. After this pretraining, the animals were assigned to three groups ($n =$

8), counterbalanced for response rate and efficiency (i.e., responses emitted per reinforcer) over the final three sessions of the VI 60-sec baseline phase.

In the critical phase of the study, one group of subjects continued to respond on a linear VI 60-sec schedule. A second group experienced the negative contingency, a conjoint linear VI 60-sec negative FR-30 (VI 60, –FR 30) schedule. On the conjoint VI 60, –FR 30 schedule, the occurrence of reinforcement was determined by a linear VI 60-sec schedule. When an interval timed out, a reinforcer became available and was stored in a bank until the next response was emitted. The timer controlling the VI schedule continued to run whether or not a response occurred. The second component of the conjoint schedule consisted of a negative FR 30 schedule. That is, a reinforcer was subtracted from the bank every time the FR value was satisfied (i.e., every 30 responses). As additional reinforcements became available, they were added to those already stored in the bank; however, only one food pellet was delivered at a time. If the subjects responded at a very high rate, the bank could potentially become negative, and no food would be delivered until the bank contained at least one pellet. A third group responded on a linear VI schedule, but rats in this group were yoked to those in the negative-contingency group with respect to reinforcement rate. The animals were yoked in pairs: each master animal from the negative-contingency group was yoked to a partner responding on a linear VI schedule. The same two animals remained paired throughout the study. Each day, the master animal first received its session with the negative component. The reinforcement frequency was then calculated over the whole session for the master subject. This determined the linear VI schedule value for the yoked partner. Reinforcement was then scheduled to occur according to this VI value (range 3 sec to three times the mean). All sessions were 40-min long for all groups. The subjects experienced their respective contingencies for 30 sessions.

Results

The mean response rates and efficiency scores over the last 3 days of pretraining for the subjects that were to become the VI group were 17.5 responses per minute and 20.8 responses per reinforcer, respectively. The equivalent scores for the subjects that were to become the negative contingency (VI-FR) animals were 18.8 responses per minute and 21.7 responses per reinforcer. The subjects that were to become the yoked VI subjects produced a mean response rate of 18.0 responses per minute, and 19.7 responses per reinforcer over the last three sessions of pretraining. An analysis of variance (ANOVA) conducted on these data revealed no group differences in either response rate ($F < 1$) or efficiency ($F < 1$).

Group mean response rates over the course of training, represented as three-session blocks, are displayed in Figure 1. Inspection of the data reveals that the VI group responded faster than the VI-FR group and the yoked VI group. By the end of training, the rate of responding of the yoked VI group, although lower than that of the simple VI group, was greater than that of the negative-contingency group.

The above description of the data was corroborated by a two-factor ANOVA, with schedule type (i.e., VI, yoked VI, and negative-component schedules) and block as factors. This analysis revealed statistically significant main effects of schedule [$F(2,21) = 4.87, p < .05$] and block [$F(9,189) = 13.72, p < .01$], and a significant interaction between these factors [$F(18,189) = 9.79, p < .01$].

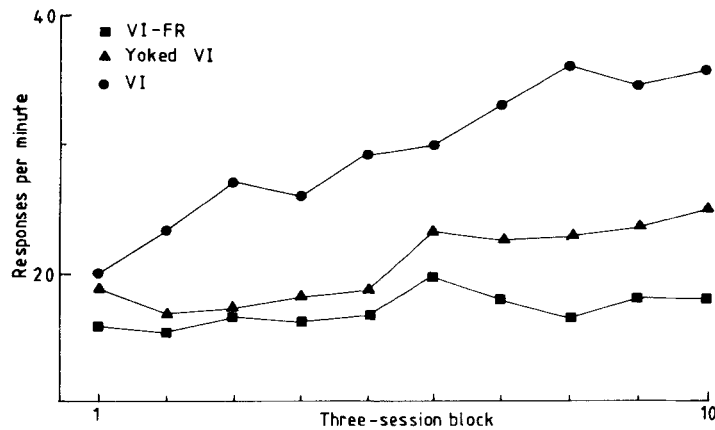


Figure 1. Mean response rates represented as three-session blocks for all three groups in Experiment 1. VI = variable interval; VI-FR = conjoint variable-interval negative fixed-ratio; Yoked VI = variable-interval schedule yoked to reinforcements received by Group VI-FR.

Specific comparisons of the terminal levels of performance over the last four three-session blocks, when responding appeared to be stable, revealed a significant effect of schedule [$F(2,21) = 19.72, p < .01$], but not of block ($p > .20$) or interaction ($F < 1$). Collapsing the data from these last four blocks, a Tukey's hsd test revealed that the VI group differed significantly from both other groups ($ps < .05$). Furthermore, the yoked VI group differed significantly from the VI-FR group ($p < .05$).

The mean number of reinforcements earned by the three groups on the first and last three-session blocks are displayed in Figure 2. Inspection of these data reveals that the yoking procedure used in the present study produced an almost identical number of reinforcements in the VI-FR and yoked VI groups, as would be expected. Both of these groups received fewer food pellets than did the VI group. The VI group earned approximately the same number of pellets on the first and last blocks. The number of pellets earned by the subjects that experienced the negative component was lower at the end than at the start of training, as was the number of rewards obtained by the yoked VI group. A two-factor ANOVA (schedule \times block) was conducted on the data in Figure 2 and revealed a significant main effect of schedule [$F(2,21) = 16.73, p < .05$] and block [$F(1,21) = 8.73, p < .05$], and an interaction of these factors [$F(2,21) = 5.64, p < .05$]. These data were further analyzed by treating the number of reinforcements earned as a within-subject factor and conducting separate ANOVAs on the first and last blocks for each group. These ANOVAs revealed a significant decline in the number of reinforcers earned for both the VI-FR group [$F(1,7) = 4.74, p < .05$] and the yoked VI group [$F(1,7) = 4.79, p < .05$]. There was no statistically reliable change in the number of reinforcers earned between the first and last blocks by animals in the simple VI group ($p > .20$).

The group mean efficiency scores, represented as three-session blocks, are displayed in Figure 3. The inefficiency of performance was pronounced in the VI-FR group, as it was in the yoked VI group, but subjects experiencing the latter schedule emitted more responses per reinforcer than did subjects receiving the former treatment. The VI group produced relatively fewer responses per reinforcer, although this score increased from 19.0 to 38.8 responses per reinforcer over the course of training, which indicates that efficiency became worse with further training as response rates increased. A two-factor ANOVA (schedule \times block) was conducted on the data represented in Figure 3. This analysis revealed statistically significant

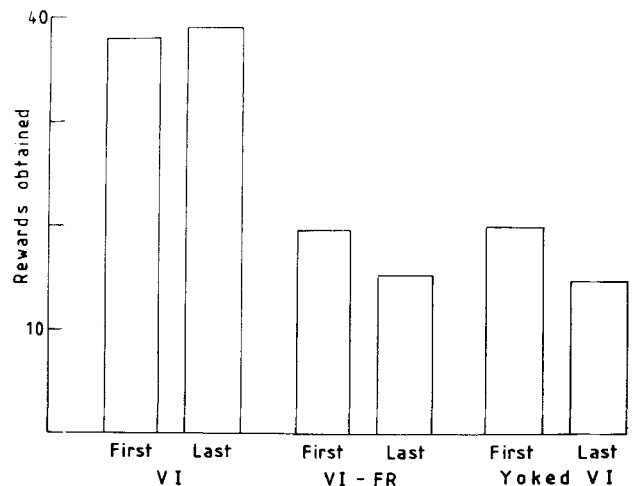


Figure 2. Mean number of reinforcers earned on the first and last three-session blocks for all three groups in Experiment 1. VI = variable interval; VI-FR = conjoint variable-interval negative fixed-ratio; Yoked VI = variable-interval schedule yoked to reinforcements received by Group VI-FR.

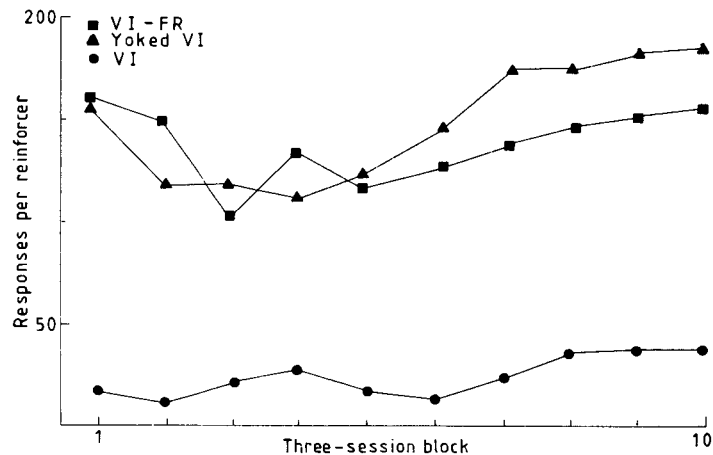


Figure 3. Mean responses per reinforcer represented as three-session blocks for all three groups in Experiment 1. VI = variable interval; VI-FR = conjoint variable-interval negative fixed-ratio; Yoked VI = variable-interval schedule yoked to reinforcements received by Group VI-FR.

main effects of schedule [$F(2,21) = 28.97, p < .001$] and block [$F(9,189) = 15.27, p < .01$], and an interaction between these two factors [$F(18,189) = 4.72, p < .05$]. An analysis of the terminal levels of performance over the last four blocks was conducted by means of a two-factor ANOVA (schedule \times block), which revealed a main effect of schedule [$F(2,21) = 17.31, p < .05$] but no main effect of block ($p > .20$) and no interaction between these two factors ($p > .20$). The data from the last four three-session blocks were collapsed, and a Tukey's hsd test was performed. This analysis revealed that the VI group differed significantly from both of the other groups ($ps < .05$). The yoked VI group also differed significantly from the negative-contingency group ($p < .05$). In addition, it is clear that all three groups developed poorer efficiency over the course of training. Using efficiency as a within-subject factor, separate ANOVAs were conducted on the efficiency data generated by the three groups on the first and last blocks of training. These analyses revealed statistically significant worse efficiency for the VI group [$F(1,7) = 6.73, p < .05$] and for the yoked VI group [$F(1,7) = 6.21, p < .05$], but the difference in efficiency between the first and last blocks for the VI-FR subjects did not reach conventional levels of significance [$F(1,7) = 3.21, .08 > p > .07$] on the last, relative to the first, block of training.

The top panel of Figure 4 presents the group mean reinforcement rate per hour as a function of the responses per minute emitted by the VI-FR group on the first and last blocks of training, along with the feedback function of the programmed schedule. Maximally efficient performance would be achieved if the data point fell at the peak of the feedback function. However, the data from the VI-FR group did not fall close to this point. In fact, over the

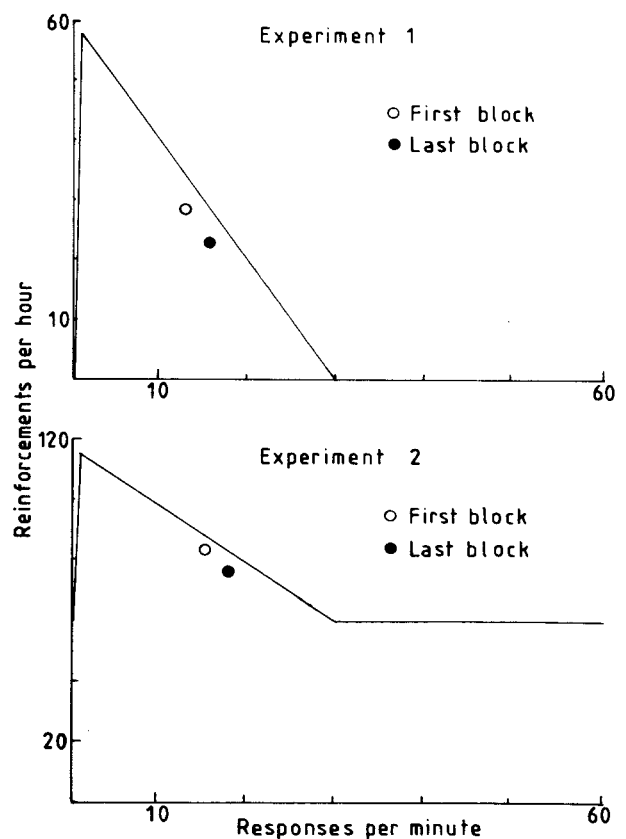


Figure 4. Group mean reinforcement rate as a function of response rate on the first (open circle) and last (closed circle) blocks of training for the negative-component group (VI-FR) in Experiment 1 (top panel) and the negative-component group (Group Negative) in Experiment 2 (bottom panel).

course of training, the subjects in this condition moved away from the point of maximum efficiency.

Discussion

The present results obtained from rats are consistent with the pattern of data reported by Vaughan and Miller (1984) for pigeons. The present study also demonstrated several findings that were not reported by Vaughan and Miller. Rates of responding were maintained by a schedule with a negative component over the course of training. The effect of the negative contingency was to decrease the number of reinforcers obtained, relative to response output, compared to a group that responded on a VI schedule without the negative component. Furthermore, the rates of responding on the negative-component schedule were found to be lower than those generated by a VI schedule that had the same frequency of reinforcement but no negative component. This finding indicates that the animals in the VI-FR group demonstrated sensitivity to some aspect of the negative schedule (see also Ettinger et al., 1987; Vaughan, 1982).

Having demonstrated the basic finding of Vaughan and Miller (1984), the predictions derived from optimization theories may be assessed. The response rates of the subjects that experienced the negative schedule did not decline over the course of training, despite a decrease in the rate of reinforcement. Thus, these subjects were responding at rates much higher than was optimal since they emitted such a large number of responses that they lost reinforcers. It is worth noting that this pattern of results was also found in the yoked VI and simple VI groups. The results of the present study pose difficulties for optimal foraging (Charnov, 1976; Lea, 1978) and maximization (e.g., Baum, 1981; Rachlin et al., 1981; Rachlin & Burkhard, 1978) theories of instrumental performance. This pattern of results reflects an increase in effort for less reinforcement, or a move away from a point of maximum value—that is, moving away from high levels of reinforcement and much leisure time. Similarly, the increase in response rate accompanied by a reduction in reinforcement frequency over the course of training would indicate a deviation from the free-behavior set point as defined by Staddon (1979).

However, it should be noted that several objections may be raised with respect to this interpretation of the data. The optimal strategy for animals responding on a negative-feedback schedule with a linear VI schedule is to withhold responding early in the session to prevent the bank from becoming negative and thus preventing subsequent food deliveries. It may be that no hungry animal would achieve this because, for the cost of a few responses, reinforcers may be earned earlier, although high response rates will prevent subsequent food deliveries. Thus, rather than a failure to optimize, rapid responding on a negative schedule may reflect a preference for immediate, as opposed to temporally distant, reinforcers (but see Thomas, 1983). Rather than examine the mechanisms underlying the lower response rate produced by the negative-component schedule relative to a matched control group,

since few investigators have noted cases in which subjects do not display optimal performance, in Experiment 2, we sought to provide further documentation of the behavior of subjects on a schedule with a negative component.

EXPERIMENT 2

Optimization theories rely on the assumption that the molar-feedback function relating response rate to reinforcement rate is crucial in allowing an animal to optimize (Baum, 1973, 1981; Rachlin et al., 1981; Rachlin & Burkhard, 1978; Staddon, 1979). Rachlin and Baum (1972) have argued that the source of reinforcement—that is, response-dependent or response-independent—does not matter in mediating the animal's performance. An increase in reinforcement frequency accompanying an increase in response rate will generate higher levels of performance. Thus, if an animal optimizes its behavior with respect to the total amount of reinforcement available, then optimal levels of performance should be produced whether the reinforcers are response-dependent or response-independent.

Thomas (1981) tested this prediction by presenting rats with a schedule in which every response was reinforced (CRF), but in which responding lowered the overall rate of reinforcement. In that study, food was delivered to rats independently of their behavior. Leverpressing also provided immediate reinforcement but canceled the next free-food presentation. Thus, responding led to a lower rate of reinforcement than did not responding. Nevertheless, as with the Vaughan and Miller (1984) experiment, despite the negative contingency between responding and the frequency of reinforcement, animals acquired the response and their levels of performance increased over the course of training. However, no yoked control groups were used by Thomas to assess the sensitivity of the animals to the schedule, or to examine the relative efficiency of responding by the critical group relative to a group lacking the food-omission component. In the present experiment, we attempted to investigate further the effects of this type of negative-component schedule.

To maintain compatibility with Experiment 1, rather than using a CRF schedule as in the Thomas (1981) study, the present experiment involved responding for food reinforcement on a (nonlinear) VI 60-sec schedule with response-independent food deliveries also programmed on an independent variable-time (VT) 60-sec schedule. As in Experiment 1, three groups of animals were included. For one group, the conjoint VI 60-VT 60 schedule was the only contingency in operation. Another group received the conjoint VI 60-VT 60 schedule and a negative component in which every 30th response canceled the next response-independent food delivery but did not affect the reinforcers programmed on the VI 60-sec schedule. A final yoked group in each session received the same number of response-dependent and response-independent food deliveries as the second group received. If subjects

maximize reinforcement rate and minimize response effort, then low response rates would be expected, since a low response rate would allow the subjects to earn reinforcers scheduled on the VI schedule and would not cancel free reinforcers programmed on the VT schedule.

Method

Subjects and Apparatus. Twenty-four male hooded Lister rats served as subjects. The rats were 4–6 months old and had an ad-lib weight range of 295–375 g at the start of the study. The animals had previously served in an appetitive classical conditioning study in which they were exposed to food pellets, a clicker, and an overhead light; however, the animals were naive with respect to leverpressing. The subjects were maintained as described in Experiment 1. The apparatus was that described in Experiment 1.

Procedure. The animals needed no magazine training, and were taught to leverpress as described in Experiment 1. Following this initial pretraining, the subjects were given one 40-min session of a VI 30-sec schedule (range 2–90 sec). After this pretraining, the animals were assigned to three groups ($n = 8$), counterbalanced for response rate and efficiency over the VI 30-sec session.

In the critical phase of the study, one group of subjects responded on a VI 60-sec schedule (range 3–180 sec). However, a second component that delivered a food pellet when an independent VT schedule timed out was added to the contingency. The mean interval value of the VT schedule was 60 sec (range 3–180 sec). Thus, a conjoint VI 60-sec VT 60-sec schedule was in operation. A second group of rats (Group Negative) also responded on this schedule except that every 30th response emitted canceled the next VT food pellet that would have been delivered. It was possible for the VT bank of reinforcements to be negative if responding reached very high levels (although, of course, the bank could not contain more than one reinforcer at a time). A third group of animals (Group Yoked VIVT) received the same scheduling arrangement as the first group (i.e., there was no negative relationship between responding and reinforcement) but the mean VI and VT values were yoked to the intervals experienced by the animals in the negative-component group. As in Experiment 1, the animals were yoked in pairs, the same pairs remaining yoked throughout the experiment. On each day, the master animal first received its session with the negative-component schedule. The average interreinforcement intervals for the response-dependent and response-independent food deliveries

across the session were then calculated, and these values became the mean intervals for the VI and VT schedules for the yoked subjects (range 3 sec to three times the mean). The subjects received their respective contingencies for 30 sessions. Each session lasted 40 min.

Results

The mean response rates and efficiency scores on the last day of pretraining were subjected to ANOVAs, which yielded no significant difference between the groups.

Figure 5 displays, in three-session blocks, the group mean response rates over the course of training. Inspection of the data reveals that the group receiving the conjoint VI 60-sec VT 60-sec schedule (Group VIVT) came to respond at a lower rate than did the group receiving the negative-component schedule (Group Negative) and Group Yoked VIVT. By the end of training, the rate of responding by Group Yoked VIVT was greater than that of Group Negative. This description was corroborated by a two-factor ANOVA (schedule \times block) conducted on the response rates displayed in Figure 5, which revealed significant main effects of schedule [$F(2,21) = 6.83$, $p < .05$] and block [$F(9,189) = 9.57$, $p < .01$], and an interaction of these two factors [$F(18,189) = 5.31$, $p < .01$]. An analysis of the terminal levels of performance over the last four three-session blocks was carried out by means of a two-factor ANOVA (schedule \times block), which revealed a significant main effect of schedule [$F(2,21) = 15.03$, $p < .01$]; however, the main effect of block and the interaction were not significant ($ps > .20$). Collapsing the data from these last four blocks, Tukey's hsd tests revealed that Group VIVT differed from each of the other groups ($ps < .05$), and that Group Negative differed from Group Yoked VIVT ($p < .05$).

The mean number of reinforcements obtained by the three groups on the first and last three-session blocks are displayed in Figure 6. Reinforcements delivered for

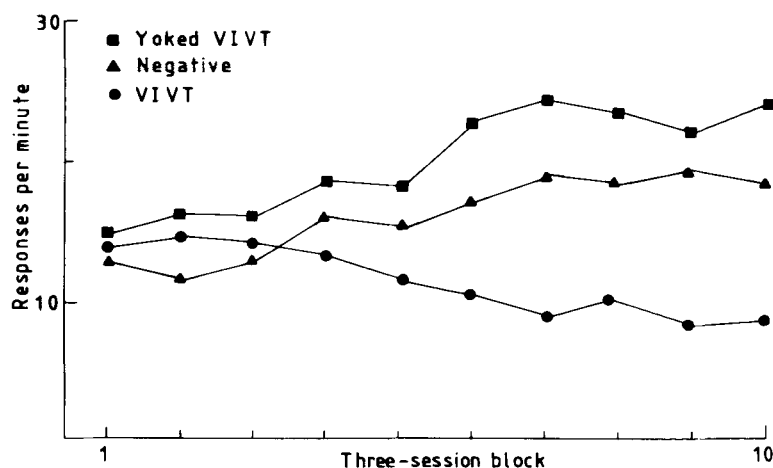


Figure 5. Mean response rates represented as three-session blocks for all three groups in Experiment 2. VIVT = conjoint variable-interval variable-time schedule; Negative = conjoint variable-interval variable-time schedule with response-independent food omitted every 30 responses; Yoked VIVT = conjoint variable-interval variable-time schedule with reinforcers yoked to those obtained in Group Negative.

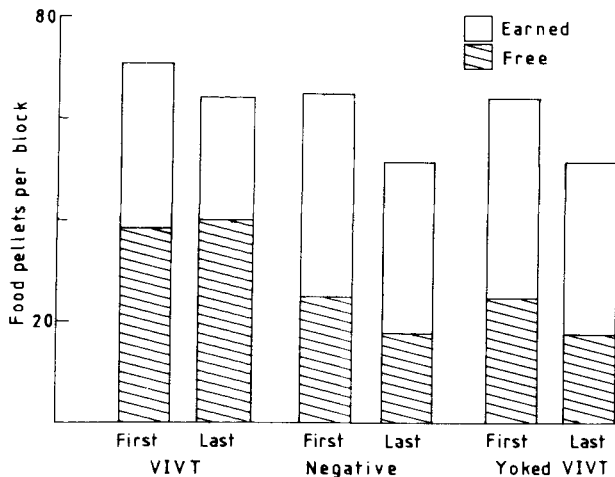


Figure 6. Mean number of reinforcers obtained on the first and last three-session blocks for all three groups in Experiment 2. Hatched portions of bars represent reinforcers obtained on the VT schedule; open portions of bars represent reinforcers earned on the VI schedule. VIVT = conjoint variable-interval variable-time schedule; Negative = conjoint variable-interval variable-time schedule with response-independent food omitted every 30 responses; Yoked VIVT = conjoint variable-interval variable-time schedule with reinforcers yoked to those obtained in Group Negative.

responding on the VI schedule (earned) are shown in the clear portion of the bar. Reinforcers delivered under the VT schedule (free) are shown in the hatched portion of the bar. An examination of the group mean totals of reinforcements received (earned plus free) by each group reveals that all three groups received fewer total reinforcers at the end of training than at the start of training. Inspection of the mean number of free reinforcers delivered to Group VIVT reveals that a similar number of pellets were received on the first and last blocks. The decline in the total number of food pellets was due to a decrease in the number of reinforcers earned under the VI schedule. This is unsurprising, given the decline in response rate over the course of training (see Figure 5). Inspection of these data for Group Yoked VIVT and Group Negative reveals that the yoking procedure used in the present study produced an identical number of free reinforcements on the first and last blocks of training; both groups received fewer free pellets than did Group VIVT. A two-factor ANOVA (schedule \times block) was conducted on the total number of reinforcers earned, and revealed a significant main effect of schedule [$F(2,21) = 7.87, p < .05$] and block [$F(1,21) = 13.63, p < .01$]. The interaction of these factors was not significant ($p < .10$). The ANOVA (group \times block) conducted on the number of free food pellets delivered revealed a significant main effect of schedule [$F(2,21) = 27.52, p < .01$] and block [$F(1,21) = 19.33, p < .01$], but no interaction between these factors ($p > .10$). The analysis conducted on the number of earned reinforcers revealed a significant main effect of schedule [$F(2,21) = 13.70, p < .01$] and block [$F(1,21) = 22.23, p < .01$], but no interaction ($p > .10$). Treating the total number of reinforcers

(earned plus free) as a within-subject factor, and conducting separate ANOVAs for each group on the first and last blocks, revealed a significant decline in the number of reinforcers for both Group Negative [$F(1,7) = 8.76, p < .05$] and Group Yoked VIVT [$F(1,7) = 8.39, p < .05$], but not for Group VIVT ($p > .20$).

The group mean efficiency scores, represented as three-session blocks, are displayed in Figure 7. The number of responses per reinforcer (earned plus free) increased during the course of training for both Group Negative and Group Yoked VIVT. The latter group responded slightly more per reinforcer than did the subjects in the former condition. In contrast, Group VIVT produced a relatively low number of responses per reinforcer during training, and its mean efficiency score decreased from 8.1 responses per reinforcer on the first block to 6.9 responses per reinforcer on the last block. A two-factor ANOVA (schedule \times block) conducted on the data represented in Figure 7 revealed statistically significant main effects of schedule [$F(2,21) = 18.07, p < .01$] and block [$F(9,189) = 11.27, p < .01$], and a significant interaction between the two factors [$F(18,189) = 6.29, p < .01$]. An analysis of the terminal levels of performance over the last four three-session blocks was conducted by means of a two-factor ANOVA (schedule \times block), which revealed a main effect of schedule [$F(2,21) = 7.31, p < .05$] but no main effect of block or interaction ($ps > .20$). Collapsing the data from these last four three-session blocks, a Tukey's hsd test revealed that Group VIVT differed from both of the other groups ($ps < .05$). Furthermore, Group Yoked VIVT differed from Group Negative ($p < .05$). Using efficiency as a within-subject factor, separate ANOVAs were conducted on the efficiency generated by the three groups on the first and last blocks of training. These analyses revealed a significant improvement in efficiency for Group Yoked VIVT [$F(1,7) = 4.73, p < .05$] but poorer efficiency for Group VIVT

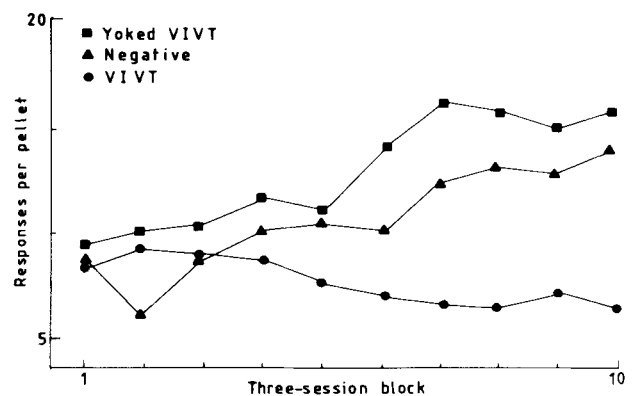


Figure 7. Mean responses per reinforcer represented as three-session blocks for all three groups in Experiment 2. VIVT = conjoint variable-interval variable-time schedule; Negative = conjoint variable-interval variable-time schedule with response-independent food omitted every 30 responses; Yoked VIVT = conjoint variable-interval variable-time schedule with reinforcers yoked to those obtained in Group Negative.

$[F(1,7) = 4.21, p < .05]$ and Group Negative $[F(1,7) = 7.81, p < .05]$.

The bottom panel of Figure 4 displays the obtained reinforcement rate as a function of the response rate for Group Negative on the first and last blocks of training. The solid line represents the programmed feedback function relating response rate to reinforcement rate. Inspection of these data reveals that the subjects in this group moved away from the point of maximal efficiency (i.e., where the greatest number of reinforcers are earned for the fewest number of responses) over the course of training.

Discussion

The subjects in Group VIVT responded at a lower rate than did the subjects in either Group Negative or Group Yoked VIVT. This may reflect the action of response-independent reinforcers on response rate. Several studies (e.g., Dickinson & Charnock, 1985; Hammond, 1980; see Burgess & Weardon, 1986, for a review) have demonstrated that response-independent reinforcers decrease response rate, and Group VIVT received more response-independent reinforcement than did either of the other two groups. Various reasons have been postulated for such an effect, for example, the reinforcement of behaviors that compete with leverpressing and/or conditioning of context-US associations that compete with response-US associations responsible for instrumental performance (Dickinson & Charnock, 1985).

As in Experiment 1, the animals were shown to be sensitive to some aspect of the negative-component schedule. That is, the animals with a negative component performed at a different rate than did the animals responding on a similar schedule (matched for the mean interreinforcement interval) but lacking the negative component. Despite this sensitivity, however, response rates in the negative-component group increased over the course of training. In turn, this increase in response rate resulted in a decrease in the number of reinforcers that this group received. Similarly, for Group Yoked VIVT, response rates increased despite no corresponding increase in the number of reinforcements received. These results are not consistent with any simple molar-optimization theory, since the animals exhibited inefficient performance with respect to maximizing reinforcements per response. As with Experiment 1, if the requirement for optimization in general regulatory models (e.g., Timberlake, 1984) is that performance should move closer to the set point, then the present finding that the negative-contingency and yoked groups moved away from the set point over the course of training is inconsistent with such views. Thus, Experiment 2 demonstrated that animals do not decrease their response output in spite of high levels of responding producing fewer reinforcements than would otherwise have been earned.

GENERAL DISCUSSION

The present experiments were designed to assess the notion common to many optimization theories that animals

maximize reinforcement rate and minimize response effort (e.g., Baum, 1981; Charnov, 1976; Rachlin et al., 1981; Rachlin & Burkhard, 1978). In both of the present experiments, the animals were found to perform inefficiently (i.e., to respond at high rates) when the contingency arranged that high rates of responding decreased the rate of reinforcement. Furthermore, in both of the present experiments, it was demonstrated that schedules with a negative component generated lower response rates than did similar schedules matched for reinforcement rate but without the negative component. Thus, the failure to optimize was reflected in increasing response rates when it was not optimal to do so, and such effects were obtained on schedules to which the subjects were found to be sensitive.

Consequently, a simple optimization assumption, such as maximal gain for minimal effort, is not adequate in accounting for the present results. However, optimization theories rely on a wide range of different mechanisms, and the present data address only those aspects of models that rely on assumptions about optimization based on the molar-feedback function. It may be possible, however, to add assumptions to optimization theories to accommodate some of the present data.

Although a simple version of optimal foraging theory (e.g., Houston & McNamara, 1985) based on maximum gain for minimum loss cannot account for the results reported here, an additional assumption can serve the theory well in addressing the present results. Collier et al. (1977) suggested that the capture of a food item by an animal may be divided into search, identification, procurement, and handling stages. It is possible that a long-term phylogenetic strategy may act to increase responding when reinforcement rate is low. That is, responses may be evoked by an absence of reward as the animal increases its search effort (see Collier et al., 1977); but in an operant chamber with the present contingencies rather than in its ecological niche, such a strategy does not achieve anything other than raising the response cost of each reinforcement.

Similarly, it is possible to add corollaries to maximization theories in light of the present studies. As mentioned in the discussion of Experiment 1, if temporally distant reinforcers do not possess the same value as proximal reinforcers (particularly with regard to choice behavior), then the inefficient behavior of the subjects may be explained. However, it should be pointed out that this addition is, in fact, a restatement of the power of molecular contingencies in determining instrumental behavior (see Thomas, 1981) and is a poor defense of a molar position. Furthermore, if an appeal to the power of contiguity is all that is needed to explain the data from Experiments 1 and 2, there would seem to be little need for the added assumptions required by optimization theories.

A general regulatory account of instrumental performance, such as that proposed by Timberlake (1984), may account for the present data in the following manner. In both of the present experiments, decreasing the rate of reinforcement increased the number of responses emit-

ted per reinforcer (i.e., efficiency deteriorated). Imposing a negative component decreased the amount of responding per reinforcer relative to the yoked control group. If it were assumed that leverpressing were highly sensitive to instances of being followed by food and was resistant to instances of responses not being followed by food, the high levels of responding generated in the negative-component group could be explained. Despite such additional assumptions that may allow regulatory theories to account for the present results, in both Experiment 1 and Experiment 2, increases in the rate of responding in the negative-component schedule over the course of training meant that behavior moved away from a behavioral set point. At the very least, this finding implies that the definition of a behavioral set point furnished by Staddon (1979)—that is, the level of performance observed on a CRF schedule—is inadequate.

In contrast to molar-optimization theories discussed above (e.g., Baum, 1981; Charnov, 1976; Rachlin et al., 1981; Timberlake, 1984), some optimization theories explicitly state that optimal performance is the result of the action of the molecular properties of a contingency on an animal's behavior (e.g., Ettinger et al., 1987; Staddon, 1983). However, if the molecular characteristics of the present schedules led to the present group differences in overall response rate, then given the effectiveness of such contingencies, performance should, according to molecular-optimization theories (e.g., Ettinger et al., 1987), have been optimal. Hence, an appeal to the molecular contingencies cannot support optimization theories.

The rejection of many optimization theories as explanations of the present results (regardless of their adequacy in explaining performance in other situations) is based upon the finding that despite the sensitivity to the operative schedule, the subjects did not perform efficiently. The sensitivity of the subjects to the schedule was taken to be reflected in the group difference in response rate between the negative-component and the yoked control conditions. It should be noted, however, that the present yoking procedure matched the overall number of reinforcers but did not match the distribution of reinforcers across the session. It is possible that this factor may have influenced the present findings, although it is difficult to explain how such a factor could have produced such consistent group differences over the course of training. Furthermore, additional studies (Reed & Schachtman, 1989) have controlled for this factor and lower rates of response were still noted in a negative-component group relative to a yoked simple VI group.

If optimization theories, as currently formulated, do not readily account for performance on the negative-component schedules employed in the present report, then it is possible that the subjects displayed sensitivity to the overall feedback functions relating response rate to reinforcement rate in a manner that does not assume that performance need necessarily be optimal (e.g., Herrnstein & Vaughan, 1980; McDowell & Wixted, 1986). There are, however, a number of studies that have demonstrated

that animals are generally not sensitive to such molar relationships (Ettinger et al., 1987; Peele, Casey, & Silberberg, 1984). Given these results, it seems unlikely that molar differences between the two contingencies are responsible for the difference in overall response rate. The molecular properties that differentiated the present schedules, and thereby likely produced the differences in performance, are not clear on the basis of the present data. Consequently, further attention should be directed at the molar differences between the schedules in accounting for the differences in performance.

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