

*EFFECTS OF REINFORCER
MAGNITUDE ON RESPONDING UNDER
DIFFERENTIAL-REINFORCEMENT-OF-LOW-RATE
SCHEDULES OF RATS AND PIGEONS*

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Experiment 1 investigated the effects of reinforcer magnitude on differential-reinforcement-of-low-rate (DRL) schedule performance in three phases. In Phase 1, two groups of rats ($n = 6$ and 5) responded under a DRL 72-s schedule with reinforcer magnitudes of either 30 or 300 μ l of water. After acquisition, the water amounts were reversed for each rat. In Phase 2, the effects of the same reinforcer magnitudes on DRL 18-s schedule performance were examined across conditions. In Phase 3, each rat responded under a DRL 18-s schedule in which the water amounts alternated between 30 and 300 μ l daily. Throughout each phase of Experiment 1, the larger reinforcer magnitude resulted in higher response rates and lower reinforcement rates. The peak of the interresponse-time distributions was at a lower value under the larger reinforcer magnitude. In Experiment 2, 3 pigeons responded under a DRL 20-s schedule in which reinforcer magnitude (1-s or 6-s access to grain) varied from session to session. Higher response rates and lower reinforcement rates occurred under the longer hopper duration. These results demonstrate that larger reinforcer magnitudes engender less efficient DRL schedule performance in both rats and pigeons, and when reinforcer magnitude was held constant between sessions or was varied daily. The present results are consistent with previous research demonstrating a decrease in efficiency as a function of increased reinforcer magnitude under procedures that require a period of time without a specified response. These findings also support the claim that DRL schedule performance is not governed solely by a timing process.

Key words: differential-reinforcement-of-low-rate schedule, interresponse time, reinforcer magnitude, bar press, key peck, rat, pigeon

Under a differential-reinforcement-of-low-rate (DRL) schedule, a response is reinforced only if that response has not occurred for at least some period of time (see Kramer & Rilling, 1970, and Malott & Cumming, 1964, for reviews). A consistent finding obtained under DRL schedules is that both the bar press of rats (e.g., Richards, Sabol, & Seiden, 1993) and the key peck of pigeons (e.g., Staddon, 1965) tend to occur before the scheduled DRL value, at least when that value is sufficiently high. The relation between the scheduled DRL value and the mean obtained interresponse time (IRT) generally is described by a power function with an exponent of less than 1.0 (Wearden, 1985). Thus, as the sched-

uled DRL value increases, the mean obtained IRT falls further and further below the scheduled DRL value. Consequently, fewer of the available reinforcers are obtained as the scheduled DRL value increases (i.e., DRL schedule performance becomes less efficient).

One interpretation of the inefficient performance obtained under DRL schedules is that animals cannot produce accurate temporal intervals. Research employing procedures suggested to better investigate timing behavior, however, indicates that animals do make accurate temporal discriminations and that this behavior is described by a linear function and not by a power function (Wearden, 1985). There are two general approaches to reconciling inefficient DRL schedule performance with the observation that animals make accurate temporal discriminations. The first hypothesizes that a portion of the responses observed under DRL schedules are generated by a nontiming process. Zeiler (1981) suggested that performance on timing tasks can be characterized as alternating between timing and emitting responses with-

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out regard to the passage of time. Taking the same approach, Wearden proposed that responding on temporal-production procedures such as DRL schedules is under the control of two separate processes, a timing process and a nontiming process. According to Wearden, timing responses are under the control of a scalar timing process (Church & Gibbon, 1982; Gibbon & Church, 1981) that accurately reflects the passage of time. Although the variables that control the emission of the nontiming responses were not specified, Jasselte, Lejeune, and Wearden (1990) suggested that they may be induced, such that they occur regardless of the timing requirement (see also Lewis & Dougherty, 1992). Key pecking and bar pressing may occur due to arousal induced by presentation of the reinforcer (Killeen, 1979) or, because the passage of time under DRL schedules occasionally is correlated with reinforcer delivery, the passage of time itself may induce responding (Lewis & Dougherty; cf. Segal, 1972; Staddon & Simmelhag, 1971). Jasselte et al. tested the hypothesis that responses other than the key peck might better be controlled under DRL schedules by reinforcing the pigeons' perching response, which may be less likely induced by food reinforcers. These authors obtained IRTs that accurately reflected the scheduled DRL value across a range of values (10 to 70 s) and offered this as support for the notion that a portion of key pecks under DRL schedules is induced. Results from both autoshaping (Brown & Jenkins, 1968) and negative automaintenance (Williams & Williams, 1969) are consistent with the assertion that the passage of time can induce responding when it occasionally is correlated with food delivery. In addition, consistent with Killeen's (e.g., 1985) claim that larger reinforcer magnitudes engender greater arousal is the finding that longer hopper durations result in higher rates of key pecking under a negative automaintenance paradigm (Balsam, Brownstein, & Shull, 1978).

The second approach to describing inefficient DRL schedule performance emphasizes the general finding that as the delay to a reinforcer increases the value of that reinforcer diminishes (e.g., Mazur, 1987). For example, Richards, Mitchell, de Wit, and Seiden (1997) found that 100 μ l of water delayed by 16 s is

equivalent in value to approximately 30 μ l of water delivered immediately (i.e., these two conditions are chosen with equal frequency). Thus, a possible interpretation of the high frequency of short IRTs under DRL schedules is that the value of the reinforcer is discounted by delay to such a large degree that it fails to maintain longer IRTs. According to this interpretation, increasing the DRL schedule value should decrease the value of the reinforcer, resulting in even poorer DRL schedule performance, a result consistently obtained across a range of DRL values. In a related description of inefficient DRL schedule performance, Monterosso and Ainslie (1999) suggested that because of an organism's imperfect "sense of time," short IRTs under DRL schedules have a small but immediate "expected reward value." Short IRTs, therefore, occur because this small but immediate expected reward value is greater than the value of the delayed reinforcer available for longer IRTs.

To summarize, there are two general interpretations for the occurrence of the relatively high frequency of IRTs too short to meet the criterion for reinforcement on DRL schedules. The first attributes subcritical IRTs to factors associated with arousal induced by reinforcer presentation and the passage of time, and the second attributes their occurrence to the degradation of reinforcer value by delay. An experimental manipulation that may differentiate between these two descriptions, and that is of interest in its own right (Beer & Trumble, 1965; Reed & Wright, 1988), is to alter reinforcer magnitude (see Bonem & Crossman, 1988, for a review). According to the first interpretation, larger reinforcer magnitudes should result in greater arousal and thus a higher frequency of responding. In contrast, the second interpretation argues (consistent with the law of effect) that larger reinforcer magnitudes better promote the occurrence of the response, or response sequence, necessary for and preceding the reinforcer presentation (e.g., Ferster & Skinner, 1957; cf. Reed & Wright, 1988). Thus, according to the second interpretation, larger reinforcer magnitudes should either decrease or at least have no effect on the frequency of responding under DRL schedules.

EXPERIMENT 1

In Experiment 1, the effects of two reinforcer magnitudes (30 and 300 μl of water) on DRL schedule responding of rats were examined in three phases. In the first phase, acquisition of responding under a DRL 72-s schedule as a function of water amount was investigated. The water amounts then were reversed for each rat. In the second phase, DRL 18-s schedule performance was examined, across conditions, as a function of the same water amounts. The third phase was identical to the second phase except that the water amounts alternated daily.

METHOD

Subjects

Twelve experimentally naive male Holtzman Sprague-Dawley rats (Harlan Sprague Dawley Inc., Indianapolis, IN) were used. Pairs of rats were housed in plastic cages in a colony room with the lights on from 7:00 a.m. to 7:00 p.m. The rats had continuous access to food in their home cages. Each rat received water during the session (see below) and for 20 min following each session. Sessions occurred 7 days per week. Because of an apparatus error the data for 1 rat were not used, so the data reported are for the remaining 11 rats.

Apparatus

Eleven operant conditioning chambers, each 20.5 cm wide, 20.5 cm deep, and 23.5 cm long, were used. Each chamber had grid floors, aluminum front and back walls, and Plexiglas sides. A lever was mounted on the front wall 3 cm above the grid floor 4.5 cm from the nearest side, and a downward force of approximately 0.15 N was required for a lever press to be recorded. Two 110-W bulbs provided general illumination. One bulb was located 3 cm above the lever, and the other was centered on the back wall 10 cm above the floor. These bulbs were lit when each session began and darkened when the session ended. Each chamber contained two water dispensers, located on the front wall, constructed to deliver distilled water into a round (1 cm diameter) plastic disk. Only the left water dispenser was used. Access to the disk was provided through a round hole (4.5 cm diameter). A Sonalert tone generator (Model

SC628, Newark Electronics) with a frequency of 2,900 cps was located 1 cm above the left water dispenser. Each chamber was enclosed in an ice chest, and fans mounted on the ice chests provided ventilation and masking noise to attenuate external stimuli. Programming and data recording were controlled by a personal computer using MED-PC[®] software (MED Associates, Inc. & Tatham, 1991).

Procedure

Each rat initially received three or four consecutive overnight training sessions under an alternative fixed-time 10-min fixed-ratio 1 schedule. Each training session lasted 10 hr or for 100 responses, whichever occurred first. The reinforcer during these training sessions was 100 μl of water. When each of the rats made 100 responses during two consecutive overnight training sessions, DRL 72-s schedule training commenced.

*Phase 1: DRL 72-s Schedule**Performance*

Under the DRL 72-s schedule, a lever press produced water only if at least 72 s had elapsed since the previous lever press, the beginning of the session, or the previous water delivery. The rats initially were trained under the DRL 72-s schedule with either 30 ($n = 6$) or 300 μl ($n = 5$) of water. This condition continued for 119 sessions during which responding stabilized, as assessed by visual inspection of each dependent variable (see below). Following this condition, the reinforcers were reversed such that each rat receiving 30 μl of water received 300 μl and vice versa. This condition continued for 84 sessions during which responding again stabilized, as assessed visually. Throughout the experiment, for some rats a 2,900-cps tone was correlated with a 30- μl water delivery, and for others the tone was correlated with a 300- μl water delivery. Sessions lasted 60 min.

*Phase 2: DRL 18-s Schedule**Performance*

In this phase, the DRL schedule was changed from 72 to 18 s while the water amounts remained as they were. The rats were divided into two new groups ($n = 6$ and 5) such that each group was comprised of 2 or 3 rats from the previous 30- and 300- μl conditions. Thus, the water amount was

changed for some rats but not for others. This initial condition of Phase 2 continued for 42 sessions, the water amounts then were reversed, and training continued for another 42 sessions. Responding was stable by the end of each of the two conditions. Each DRL 18-s schedule session lasted 15 min to keep the possible number of reinforcers per session constant at 50 between Phases 1 and 2.

*Phase 3: DRL 18-s Schedule
Performance Under Daily
Reinforcer-Magnitude Alternation*

This phase was identical to Phase 2 with the exception that, for each rat, the water amounts now alternated each session. This final phase continued for 30 sessions.

Data Analysis

Six measures of performance were analyzed: reinforcers per hour, total responses per hour, pause responses per hour, burst responses per hour, peak location (PkL), and peak area (PkA). The PkL and PkA metrics were developed to quantify the profile of DRL IRT distributions (Richards et al., 1993; Richards & Seiden, 1991). PkL and PkA metrics are computed by comparing each rat's obtained IRT distribution to a theoretical distribution that predicts the appearance of the obtained IRT distribution had the rat emitted responses at the same overall rate, but randomly in time with respect to the preceding response. This expected random curve is called the *corresponding negative exponential* and is based on the mean of the obtained IRT durations with bursting (see below) excluded.

Derivation of PkL and PkA are illustrated by the relative frequency histogram in Figure 1 (column 1, row 4). The IRT distributions of rats under DRL schedules are frequently bimodal, with one mode occurring at the shorter IRT durations (burst distribution) and a second mode occurring at longer IRT durations (pause distribution). The leftmost single shaded histogram bar indicates the burst component of the IRT distribution (IRTs < 6 s). The bars to the right of the burst component indicate the pause component of the IRT distribution (IRTs ≥ 6 s). The connected filled circles indicate the appearance of the pause component of the IRT distribution if the rats emitted the same number of responses, but randomly in time with

respect to the preceding response (corresponding negative exponential). The PkA is the area of the obtained IRT distribution above the corresponding negative exponential and is indicated by the shaded region. The PkL is the median IRT duration that bisects the shaded region above the corresponding negative exponential. The filled triangle in the burst category indicates the relative frequency of burst responses predicted by extrapolation of the corresponding negative exponential into the burst component. The single filled circle at the far right indicates the relative frequency of IRTs > 144 s predicted to occur in the tail of the corresponding negative exponential. Similarly, the rightmost single histogram bar indicates the relative frequency of IRTs > 144 s in the tail of the obtained IRT distribution. For the DRL 18-s schedule, IRTs < 1.5 s were defined as burst responses, and IRTs were separated into 1.5-s bins. An empirical justification of these criteria is in Richards et al. (1993).

To determine if the reinforcer magnitudes produced statistically significant differences, within-subject *t* tests were conducted by combining the data from the last 2 weeks of each condition for Phases 1 and 2. In this way, the data from each rat at each magnitude could be included for a more representative group mean. An analysis comparing the effects of alternating reinforcer magnitudes also was conducted for the last 2 weeks of Phase 3. For all statistical analyses, the criterion for significance was set at $p < .05$.

RESULTS AND DISCUSSION

*Phase 1: DRL 72-s Schedule
Performance*

Distributions of IRTs obtained during Weeks 1, 3, 6, and 17 under the DRL 72-s schedule for each reinforcer-magnitude group are shown in Figure 1. IRT relative frequencies are plotted in 6-s bins, and the obtained PkA and PkL are listed in each graph. The histogram bars indicate the obtained IRTs, and the filled circles indicate the corresponding negative exponential. During Week 1, the obtained distributions for both groups were similar to the corresponding negative exponential, indicating that the IRTs

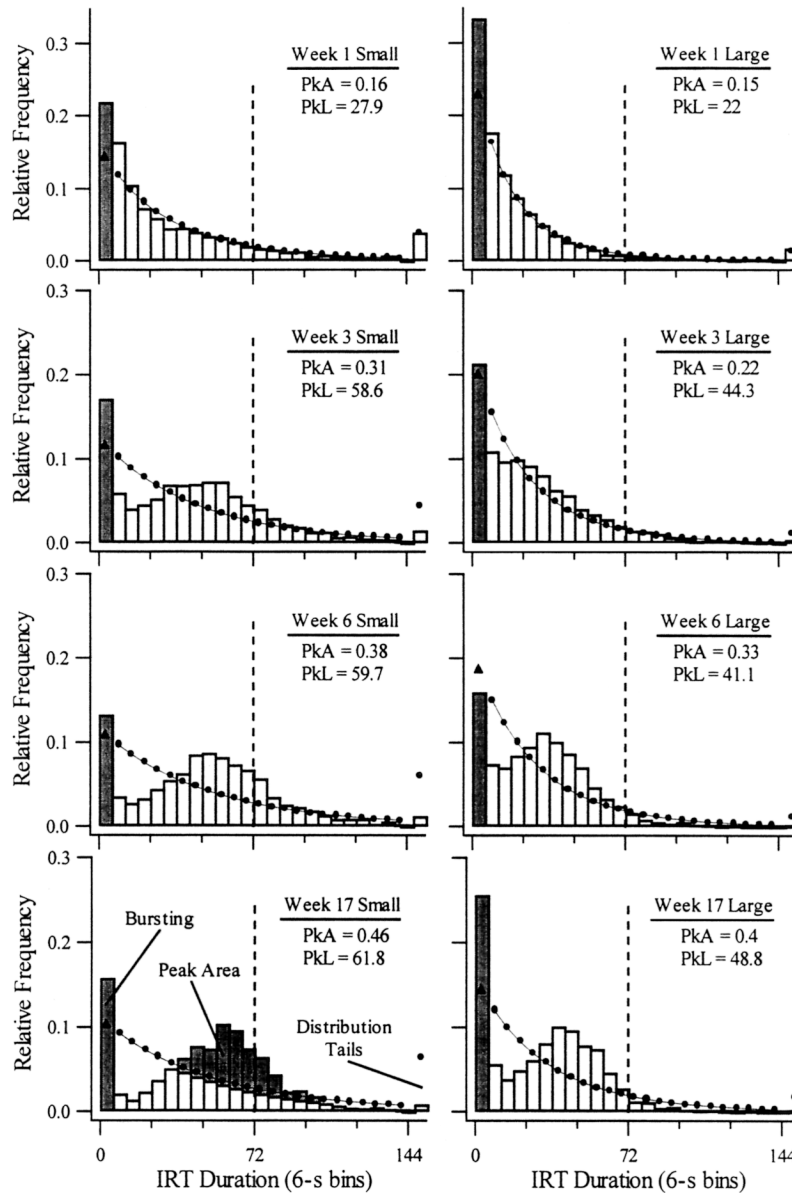


Fig. 1. IRT distributions from small (left graphs) and large (right graphs) reinforcer-magnitude groups during Weeks 1, 3, 6, and 17 of the initial DRL 72-s schedule. Mean PkA and PkL are listed in each graph. See text for details.

were randomly distributed. At Week 3, the obtained distribution of IRTs for the small-reinforcer group became differentiated from the corresponding negative exponential. In contrast, the large-reinforcer group showed less differentiation. At Week 6, both groups were differentiated from the corresponding negative exponential. The small-reinforcer group had a PkL that was closer to 72 s. At

Week 17, the IRT distributions of both groups were differentiated from the random prediction provided by the corresponding negative exponential. The obtained IRT distribution of the small-reinforcer group had a greater PkL and was more differentiated from the corresponding negative exponential than the large-reinforcer group. In summary, the IRT distribution of the small-reinforcer group

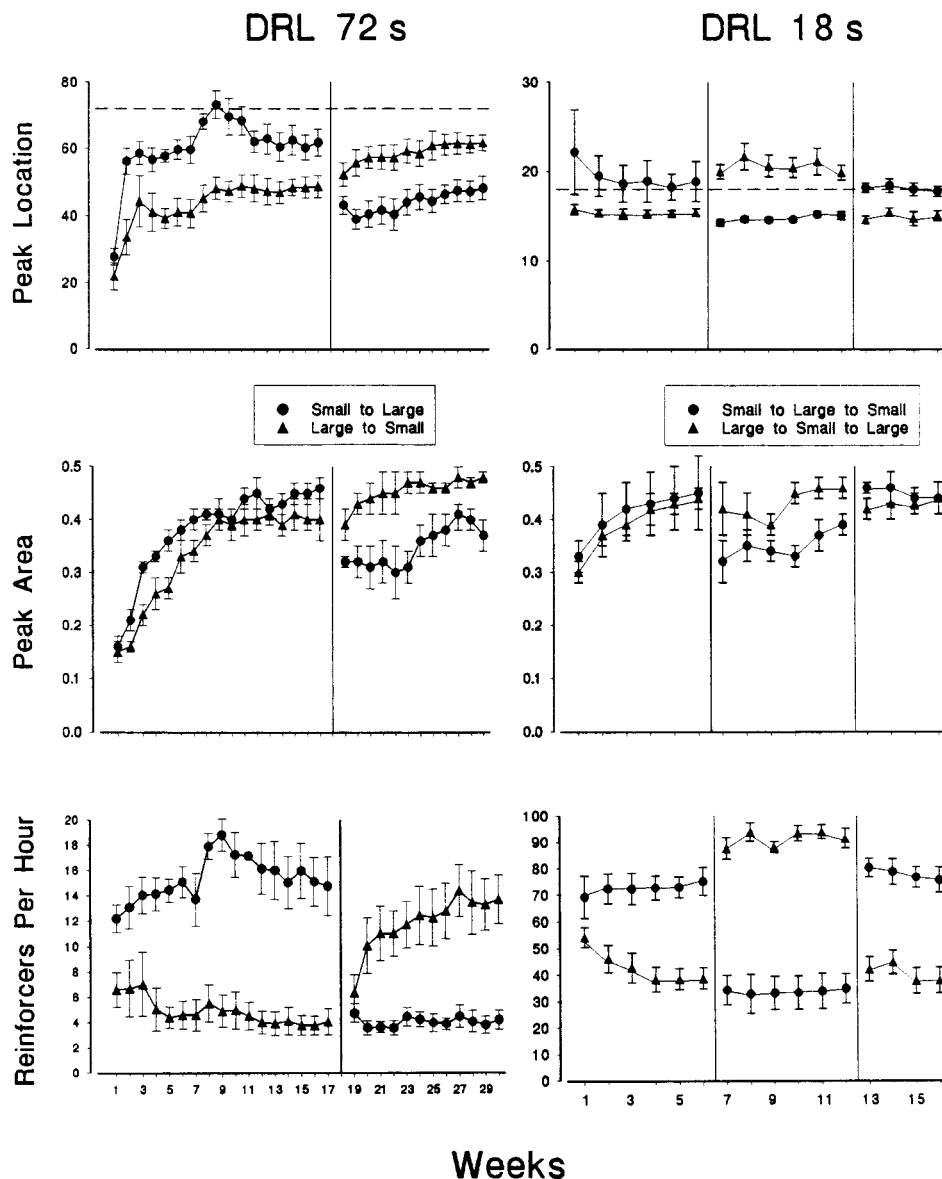


Fig. 2. Mean PkL (top graphs), PkA (middle graphs), and reinforcers obtained per hour (bottom graphs) for each reinforcer-magnitude group across weeks under the DRL 72-s (left graphs) and DRL 18-s (right graphs) schedules. Error bars show standard errors of the mean.

showed both more rapid and larger deviations from the corresponding negative exponential than the IRT distribution of the large-reinforcer group. The data for individual rats at Weeks 1, 3, 6, and 17 of Phase 1 are listed in Appendix A.

The above description of both acquisition and steady-state responding provided by the IRT histograms is supported by the data pro-

vided in the left graphs of Figures 2 and 3. The vertical line in each of the left graphs indicates the point at which the reinforcer magnitudes were reversed, and the horizontal dotted line in the top graph of Figure 2 shows the 72-s criterion. Higher PkL, $t(10) = 10.996$, $p < .001$, and PkA, $t(10) = 4.175$, $p < .01$, values were obtained with the 30- μ l reinforcer than with the 300- μ l reinforcer. A

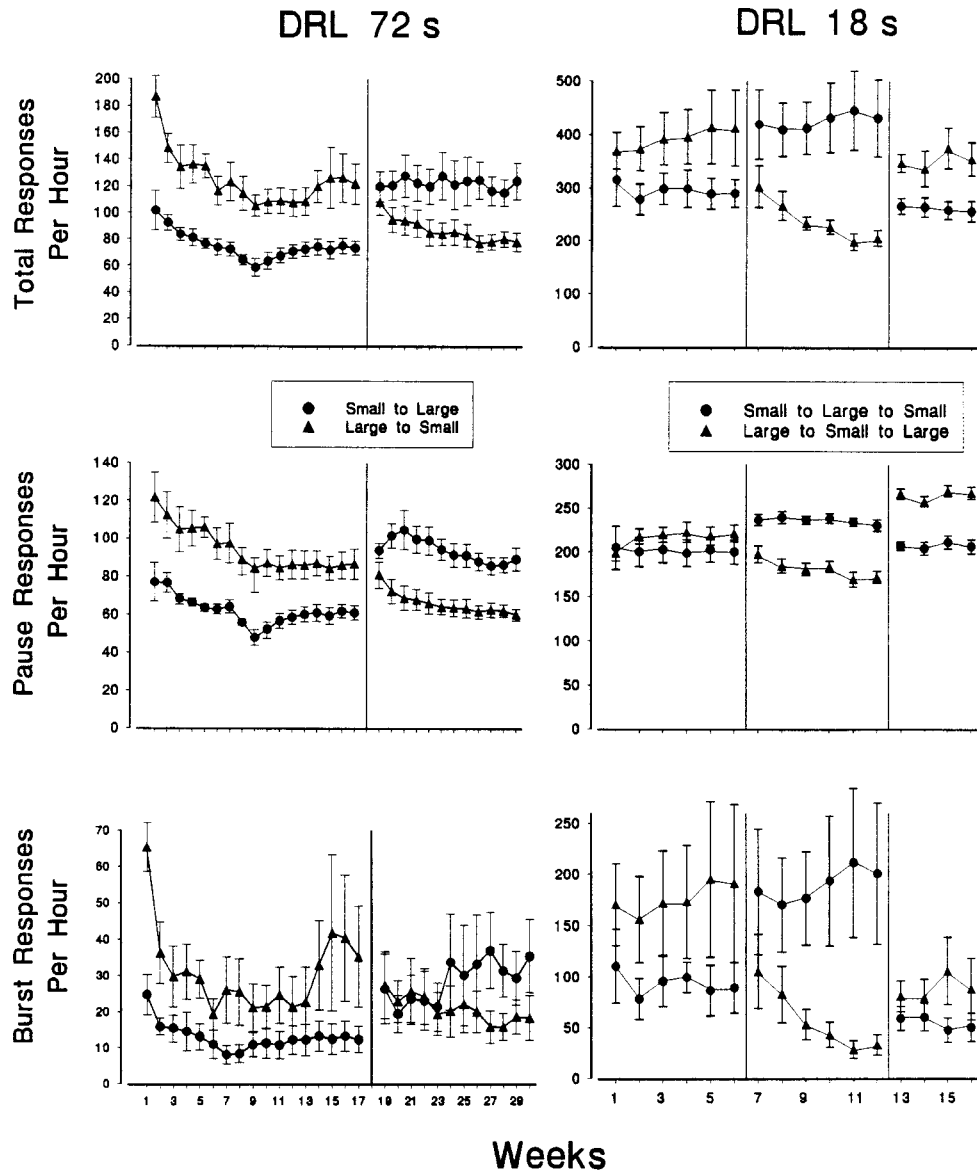


Fig. 3. Mean total (top graphs), pause (middle graphs), and burst (bottom graphs) responses per hour for each reinforcer-magnitude group across weeks under the DRL 72-s (left graphs) and DRL 18-s (right graphs) schedules. Error bars show standard errors of the mean.

greater mean number of reinforcers was obtained with the 30- μ l reinforcer, $t(10) = 10.192$, $p < .001$, than with the 300- μ l reinforcer. Greater total, $t(10) = -6.138$, $p < .001$, pause, $t(10) = -10.404$, $p < .001$, and burst, $t(10) = -3.129$, $p < .05$, response rates occurred with the 300- μ l reinforcer than with the 30- μ l reinforcer.

Individual rats' data for all six dependent measures during the last 2 weeks at each re-

inforcer magnitude in Phase 1 are provided in Appendix B.

Phase 2: DRL 18-s Schedule Performance

The right graphs of Figures 2 and 3 show the three separate conditions. The first vertical line indicates the point at which the reinforcer magnitudes were reversed, and the second vertical line indicates the point at

which they began to alternate daily. The data from Phase 3 are described separately below. The horizontal dotted line in the top graph of Figure 2 shows the 18-s criterion. Higher PkL values were obtained with the 30- μ l reinforcer than with the 300- μ l reinforcer, $t(10) = 10.996$, $p < .001$. There was no statistically significant difference in the PkA values ($p > .05$). Reinforcement rate was higher with the 30- μ l reinforcer than with the 300- μ l reinforcer, $t(10) = -3.872$, $p < .01$. Total, $t(10) = -6.138$, $p < .001$, pause, $t(10) = -10.404$, $p < .001$, and burst, $t(10) = -5.317$, $p < .001$, response rates were higher with the 300- μ l reinforcer than with the 30- μ l reinforcer.

Individual rats' data for all six measures during the last 2 weeks at each reinforcer magnitude in Phase 2 are provided in Appendix B.

*Phase 3: DRL 18-s Schedule
Performance Under Daily
Reinforcer-Magnitude Alternation*

The effects of alternating reinforcer magnitudes each session are depicted in the last section of the right graphs of Figures 2 and 3. Higher PkL values were obtained with the 30- μ l reinforcer than with the 300- μ l reinforcer, $t(10) = 3.399$, $p < .007$. There was no statistically significant difference in the PkA values ($p > .05$). Reinforcement rate was higher with the 30- μ l reinforcer than with the 300- μ l reinforcer, $t(10) = 6.044$, $p < .001$. Greater total, $t(10) = -3.997$, $p < .01$, and pause, $t(10) = -7.701$, $p < .001$, response rates were obtained with the 300- μ l reinforcer than with the 30- μ l reinforcer. There was no statistically significant difference in burst response rates ($p > .05$).

Individual rats' data for all six dependent measures during the last 2 weeks of Phase 3 are provided in Appendix B.

To summarize, extended training under the DRL 72-s schedule with small and large reinforcer magnitudes resulted in differences in PkL, PkA, reinforcement rate, and rates of responding. IRT distributions with characteristically different profiles as a function of the reinforcer magnitudes were evident. Lower response rates, higher reinforcement rates, and IRT distributions better approximating "optimal" performance were obtained with the smaller reinforcer magnitude. These effects produced by the different reinforcer

magnitudes also were obtained under the DRL 18-s schedule, regardless of whether the reinforcer magnitudes alternated between conditions (Phase 2) or sessions (Phase 3). A notable difference between responding under the two DRL schedules was that the mean PkL for the small-reinforcer group under the DRL 18-s schedule was at or above 18 s, whereas under the DRL 72-s schedule and the same reinforcer magnitude, the mean PkL was lower than 72 s. This latter finding replicates past DRL schedule research (e.g., Staddon, 1965) demonstrating less efficient DRL schedule responding as the scheduled DRL value increases.

That each rat was exposed to the two DRL schedule values in the same order may raise the question of whether similar effects would be obtained under the DRL 18-s schedule in the absence of such a lengthy exposure to the DRL 72-s schedule. Although it cannot be stated without question that this history did not alter DRL 18-s schedule responding, several features of the experiment minimized the likelihood of order effects. First, each rat received exposure to each reinforcer magnitude under the DRL 72-s schedule. Second, the order of the magnitudes received under the DRL 18-s schedule differed among rats. Third, each rat responded under the DRL 18-s schedule for a lengthy period of time. Fourth, that the reinforcer magnitudes alternated daily in Phase 3 makes it seem less likely that any lingering effects of the DRL 72-s schedule training were somehow responsible for the results.

The present findings support an interpretation of inefficient DRL schedule responding as resulting from the influence of factors associated with arousal induced by reinforcer presentation and the passage of time (Jassette et al., 1990; Killeen, 1979; Lewis & Dougherty, 1992) rather than by degradation of reinforcer value by increasing delay. Experiment 2 investigated this further in pigeons.

EXPERIMENT 2

The second experiment assessed the generality of the findings obtained in Experiment 1 by examining the effects of two reinforcer magnitudes (1-s and 6-s access to grain) on DRL 20-s schedule responding of

pigeons. As in Phase 3 of the first experiment, the different hopper durations were varied between sessions rather than conditions.

METHOD

Subjects

Three male White Carneau pigeons, with a history of key pecking on various reinforcement schedules, were maintained at approximately 80% of their free-feeding body weights. Lights were on in the colony room from 7:00 a.m. to 7:00 p.m., and water and health grit were available continuously in each home cage. Each pigeon was fed mixed grain following its session, if necessary, to maintain its target weight. Sessions occurred 7 days per week.

Apparatus

An operant conditioning chamber, with a work area 35 cm high by 30 cm wide by 30 cm long enclosed in a sound-attenuating box was used. Two response keys (2 cm diameter) were located on the front wall, 25 cm above the floor, and 10 cm from the side wall. Only the left key was used. The key was transilluminated green or red by 28-V DC bulbs, except during reinforcement. Reinforcement was the delivery of mixed grain in a food hopper located behind a feeder aperture (5 cm square) centered on the front wall with its lower edge 5 cm above the floor. The aperture was illuminated white by a 28-V DC bulb only during reinforcer availability. A fan mounted on the box provided ventilation and masking noise to attenuate external stimuli. Programming and data recording were controlled by a personal computer using MED-PC® software (MED Associates, Inc. & Tatham, 1991).

Procedure

Because of each pigeon's key-pecking history, the experiment proper commenced immediately. During each session, a DRL 20-s schedule was in effect such that food was delivered following a key peck only if at least 20 s had elapsed since the previous key peck, the beginning of the session, or the previous food delivery. The stimuli (i.e., key color and hopper duration) to be presented during each session were chosen randomly, with the only restriction being that the same stimuli could not occur on four consecutive sessions.

The key was transilluminated a single color throughout each session. When the key was green, the reinforcer was 1-s access to grain; when it was red, the reinforcer was 6-s access to grain. Training continued until responding stabilized, as assessed by visual inspection (i.e., no systematically increasing or decreasing trend in response and reinforcement rate for at least six consecutive sessions). The final number of sessions with the 1-s reinforcer for Pigeons 405, 408, and 485 were 43, 42, and 46, respectively. The number of sessions with the 6-s reinforcer were 43, 44, and 46 for Pigeons 405, 408, and 485, respectively. Each session lasted 60 min.

Data Analysis

For each pigeon, the mean number of responses emitted and reinforcers obtained (per minute) were calculated for the last six sessions under each reinforcer magnitude. For the calculation of both measures, reinforcement time (i.e., when the hopper was activated) was excluded.

RESULTS AND DISCUSSION

Figure 4 shows obtained mean reinforcement and response rate during the final six sessions under each reinforcer magnitude for each pigeon. For each pigeon, response rates were lower and reinforcement rate was higher when the reinforcer was smaller (i.e., 1-s rather than 6-s access to grain). This finding is consistent with the results of Experiment 1 that larger reinforcer magnitudes result in less efficient DRL schedule performance than smaller ones. Taken together, these findings support an interpretation of inefficient DRL schedule responding based on factors associated with arousal induced by reinforcer presentation and the passage of time (Jasseltte et al., 1990; Killeen, 1979; Lewis & Dougherty, 1992).

GENERAL DISCUSSION

The results of the present study demonstrate that larger reinforcer magnitudes result in less efficient DRL schedule performance than smaller ones. This finding was obtained with water maintaining rats' lever pressing and food maintaining pigeons' key pecking. In addition, this finding was obtained when reinforcer magnitude was varied both be-

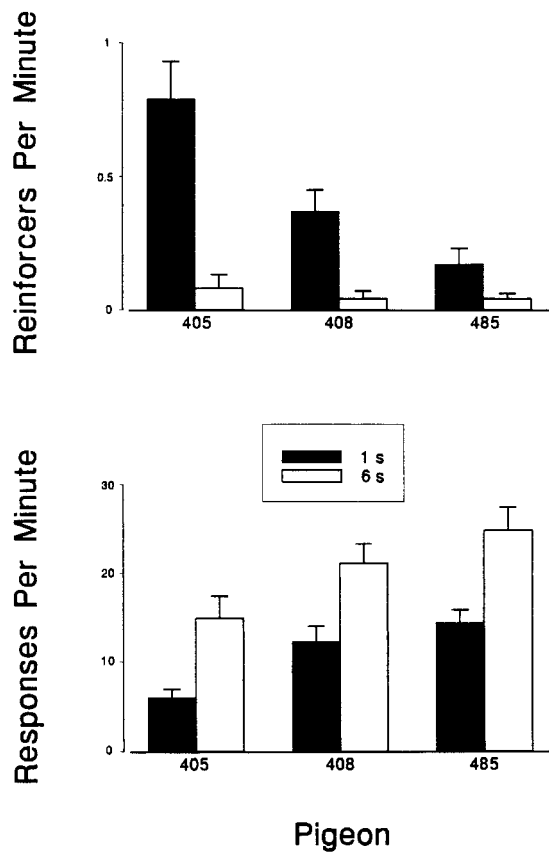


Fig. 4. Mean reinforcers (top graph) and responses (bottom graph) per minute across the last six sessions under each reinforcer magnitude for each pigeon under the DRL 20-s schedule. Error bars show standard deviations.

tween conditions (Experiment 1, Phases 1 and 2) and sessions (Experiment 1, Phase 3 and Experiment 2). Thus, these results have implications for interpretations of DRL schedule performance and for descriptions of reinforcer-magnitude effects on the DRL schedule and related procedures.

That efficiency of DRL schedule performance was altered by reinforcer magnitude in the present experiments is further indication that different processes underlie DRL schedule responding compared to responding under other so-called timing procedures (see Wearden, 1985). MacEwen and Killeen (1991) obtained little difference in pigeons' timing as a function of hopper duration (across values of 1, 3, and 7 s) under the peak-interval procedure. In Experiment 2 of the present study, however, reinforcer mag-

nitudes similar to theirs (1 and 6 s) differentially affected pigeons' responding under a DRL 20-s schedule. Further support for the assertion that the variables controlling IRT duration in DRL schedule responding are different from those in other procedures used to measure timing was found by Reynolds (1966). Reynolds required pigeons to peck a red key twice (i.e., an IRT occurred). Following the second red-key peck, the key changed to blue for 30 s and pecks to it were reinforced under a variable-interval (VI) schedule if the obtained IRT in red was greater than 18 s. Blue-key response rates were an increasing function of the obtained IRT in red; that is, the pigeons accurately discriminated their obtained IRT duration. Despite this accurate temporal discrimination, efficient red-key responding did not occur, in that few IRTs greater than 18 s were obtained. Thus, it is unlikely that DRL schedule responding is controlled by a single timing process.

An interpretation of inefficient DRL schedule responding positing that reinforcer value is so diminished by the long delay to reinforcement that it fails to maintain longer IRTs is not supported by the present results. Presumably increasing the magnitude of the reinforcer available for these longer IRTs should result in better DRL schedule responding (see Monterosso & Ainslie, 1999). This result, however, did not occur. Instead, an interpretation for such inefficient responding as a result of arousal induced by reinforcer presentation and the passage of time (Jasseltte et al., 1990; Killeen, 1979; Lewis & Dougherty, 1992) better accounts for the present results. This latter interpretation is consistent with the findings reported by Lewis and Dougherty, who demonstrated that the response rates of pigeons under VI schedules employing an omission contingency, such that a response was reinforced only if some variable duration of time had elapsed since the last response, were higher at more severe food-deprivation levels. The present results also extend those of Balsam et al. (1978), who reported higher response rates under a negative automaintenance procedure with longer rather than shorter hopper durations. Both the DRL schedule and the negative automaintenance preparation require the absence of a specified response for at least some

period of time. In general then, as “motivation” is enhanced under procedures requiring periods of not-responding, either by increasing reinforcer magnitude (Balsam et al. and the present study) or deprivation (Lewis & Dougherty), performance becomes less efficient.

Previous manipulations of reinforcer magnitude on DRL schedule performance have produced mixed results (Beer & Trumble, 1965; Reed & Wright, 1988). Reed and Wright reported that increasing the number of food-pellet reinforcers (across conditions) decreased DRL response rates and increased variable-ratio (VR) response rates under chained DRL 8-s VR 45 schedules. Whereas the results of Reed and Wright are inconsistent with those of the present study, Beer and Trumble obtained results in accord with those reported here. Beer and Trumble varied the number of food-pellet reinforcers for rats responding under DRL 20-s schedules within a session and obtained lower efficiency ratios (reinforced responses divided by total responses) as the number of pellets increased. Because Reed and Wright included their DRL schedule as part of a complex schedule their results may be due to reinforcer magnitude interacting with other variables. For example, any response-rate-increasing effect of the larger reinforcer magnitude may have been masked by examining DRL schedule responding during the initial link of a chained schedule, which is a discriminated period of nonreinforcement (e.g., Leung & Winton, 1985). Research comparing responding under chained DRL VR and chained VR DRL schedules as a function of reinforcer magnitude would assess directly any interaction between such factors.

Quantitative analysis of the IRT distribution indicated that the DRL 72-s schedule gradually altered the shape of the IRT distribution (Figure 1). The peaked shape emerged after 6 weeks of training (Figure 1), yet these changes were accompanied by only small changes in response rate (Figure 3). Quantitative analysis of the IRT distribution also revealed three observations of the reinforcer-magnitude effects. First, the differential effect of reinforcer magnitude on response rate could not be attributed solely to differences in bursting. Second, PkL differences, as a function of reinforcer magnitude,

were relatively larger under the DRL 72-s schedule than under the DRL 18-s schedule. Third, PkA values differed as a function of reinforcer magnitude under the DRL 72-s schedule but were similar under the DRL 18-s schedule, regardless of whether reinforcer magnitude varied between conditions (Phase 2) or sessions (Phase 3). These latter two findings suggest that the larger reinforcer magnitude was more disruptive when reinforcer rate was lower. These observations, along with others (e.g., Richards et al., 1993), demonstrate the utility of quantifying IRT distributions resulting from DRL training.

Performance on DRL schedules depends on response topography. In contrast to the poor performance obtained from key pecking, pigeons performing a perching response produced IRT distributions that were described well by scalar timing theory (Jasselte et al., 1990). Disruptive effects of reinforcer magnitude may occur primarily when the reinforcer induces the operant response, as is the case with bar pressing and key pecking. A perching response maintained by a DRL schedule may not be disrupted by increases in reinforcer magnitude or perhaps even may be brought under better schedule control by a larger reinforcer magnitude. The disruptive effects of larger reinforcer magnitudes on DRL schedule responding may be similar to examples of “misbehavior” described by Breland and Breland (1961), in which behavior that animals normally used to obtain food interfered with the target response that was being conditioned. Bar pressing of rats and key pecking of pigeons under DRL schedules may differ from this kind of misbehavior only in that the interfering and target responses under the DRL schedule are similar.

To our knowledge, the effects of reinforcer magnitude on DRL schedule performance in humans have not been investigated. It is unclear if effects similar to those obtained in the present study would occur with humans. Dews and Morse (1958) assessed the effects of amphetamine on adults' telegraph-key presses maintained by nickel deliveries under a DRL schedule (values of 2.5 and 25 s) that had to be completed a given number of times (i.e., a second-order fixed-ratio DRL schedule). Amphetamine did not decrease reinforcement rate, although it did increase response rate slightly. Comparison of the IRT

distributions indicated that amphetamine consistently increased responding in the time bin immediately after the criterion for reinforcement (i.e., the most optimal time to respond). In rats, the effects of amphetamine on the IRT distribution, response rate, and reinforcement rate are similar to those observed in the current study following increases in reinforcer magnitude (e.g., Richards et al., 1993). The absence of similarity in the effects of amphetamine on DRL schedule responding of rats and humans may indicate that changes in reinforcer magnitude also may not have similar effects in these species. Responses typically used in human laboratory conditioning experiments (e.g., hand movements and vocalizations) seem unlikely to be induced by money, points, tokens, or even food. It is possible that some combinations of responses and reinforcers would result in the same reinforcer-magnitude effects on human DRL schedule performance as observed in the present study. In humans, the failure to wait due to arousal or the induction of disruptive conditioned responses may be characterized as “compulsive” behavior that occurs despite the individual’s “best interest.” Van Den Broek, Bradshaw, and Szabadi (1987) found differences in DRL schedule performance in individuals who had been diagnosed as impulsive compared to those without such a diagnosis. Thus, one may speculate that such compulsive behavior may occur in obese individuals, alcoholics, and cigarette smokers who fail to maintain low rates of eating, drinking, and smoking.

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APPENDIX A

Obtained PKL, PKA, reinforcers per hour (RF), total responses per hour (TR), pause responses per hour (PR), and burst responses per hour (BR) during Weeks 1, 3, 6, and 17 under the initial DRL 72-s schedule for each rat. Each value is the mean of seven sessions. NA signifies that the peak deviation analysis was not conducted because of an insufficient number of responses (see Richards et al., 1993).

	Small-magnitude (30 μ l) reinforcer						Large-magnitude (300 μ l) reinforcer				
	Rat 1	Rat 2	Rat 3	Rat 4	Rat 5	Rat 6	Rat 7	Rat 8	Rat 10	Rat 11	Rat 12
Week 1											
PKL	NA	27.7	27.5	23.7	37.0	23.4	36.4	19.6	16.1	13.7	24.1
PKA	NA	0.17	0.20	0.11	0.18	0.16	0.18	0.11	0.11	0.20	0.16
RF	12.4	15.0	14.4	7.57	11.0	12.7	10.6	4.2	5.6	9.2	3.6
TR	80.4	66.4	90.7	167.3	119.0	86.4	161.6	233.4	207.3	147.3	185.6
PR	53.4	52.9	70.9	118.6	90.3	75.3	83.6	151.4	141.0	96.4	135.7
BR	26.7	13.5	19.8	48.7	28.7	11.1	78.0	82.0	66.3	50.9	49.9
Week 3											
PKL	62.4	56.7	58.0	46.0	57.2	71.6	59.6	29.5	27.24	63.6	41.4
PKA	0.27	0.28	0.36	0.31	0.33	0.30	0.28	0.18	0.22	0.17	0.25
RF	14.3	14.7	15.0	9.15	11.4	19.6	13.9	2.0	3.6	12.4	3.3
TR	102.6	81.6	71.6	89.6	86.6	70.3	99.6	194.3	136.9	116.3	124.4
PR	69.1	68.7	60.7	79.6	70.4	61.4	71.4	134.3	124.3	84.1	108.4
BR	33.5	12.9	10.9	10.0	16.2	8.9	28.2	60.0	12.6	32.2	16.0
Week 6											
PKL	48.2	66.2	56.5	57.4	64.1	66.0	37.5	31.0	37.5	55.5	43.9
PKA	0.38	0.37	0.40	0.38	0.29	0.43	0.30	0.28	0.29	0.37	0.41
RF	10.3	17.6	14.0	13.3	17.6	17.7	4.1	1.9	3.3	8.4	5.3
TR	101.3	64.3	66.7	68.9	78.9	62.3	120.6	154.7	112.7	99.6	94.2
PR	73.3	57.4	64.1	63.9	62.3	56.0	99.6	122.7	103.7	74.7	84.9
BR	28.0	6.9	2.6	5.0	16.6	6.3	21.0	32.0	9.0	24.9	9.3
Week 17											
PKL	46.5	75.5	57.8	63.24	59.1	68.9	52.9	38.5	43.6	54.7	54.1
PKA	0.40	0.45	0.44	0.48	0.46	0.55	0.35	0.28	0.49	0.46	0.46
RF	6.9	23.6	11.7	14.9	13.4	18.0	3.7	0.71	3.4	5.7	6.7
TR	97.4	77.0	64.6	61.3	75.3	64.7	165.1	138.7	93.6	129.4	82.9
PR	78.4	51.3	63.1	56.4	61.4	55.7	83.7	118.1	80.3	76.3	74.9
BR	19.0	25.7	1.5	4.9	13.9	9.0	81.4	20.6	13.3	53.1	8.0

APPENDIX B

Obtained PkL, PkA, reinforcers per hour (RF), total responses per hour (TR), pause responses per hour (PR), and burst responses per hour (BR) during the last 2 weeks at each reinforcer magnitude in each phase of Experiment 1 for each rat. Each value is the mean of 14 sessions. Values in bold were tested first.

	Rat 1	Rat 2	Rat 3	Rat 4	Rat 5	Rat 6	Rat 7	Rat 8	Rat 10	Rat 11	Rat 12
Phase 1: DRL 72-s schedule											
Small-magnitude (30 μ l) reinforcer											
PkL	45.9	71.1	56.4	63.1	60.2	69.8	68.4	54.8	57.5	64.8	62.1
PkA	0.44	0.44	0.45	0.46	0.44	0.55	0.48	0.44	0.49	0.48	0.49
RF	6.9	20.4	12.2	16.0	14.9	19.1	17.3	6.4	12.0	16.5	15.1
TR	96.7	79.3	66.6	61.6	79.9	61.5	93.5	93.1	71.9	77.6	61.4
PR	77.6	47.1	64.0	58.1	60.4	54.0	57.2	73.1	61.9	56.9	56.2
BR	19.1	32.2	2.6	3.5	19.5	7.5	36.3	20.0	10.0	20.7	5.2
Large-magnitude (300 μ l) reinforcer											
PkL	38.5	59.9	46.5	42.7	45.3	54.7	52.63	38.8	43.4	54.1	54.2
PkA	0.38	0.44	0.39	0.41	0.41	0.42	0.36	0.29	0.49	0.42	0.45
RF	2.0	6.2	3.7	2.7	3.5	5.8	3.4	1.1	3.7	5.0	6.4
TR	136.6	92.4	92.1	119.1	168.4	112.0	175.6	137.6	93.8	130.5	83.4
PR	103.1	73.1	85.9	89.6	98.4	76.3	84.3	115.4	81.0	76.1	75.1
BR	33.5	19.3	6.2	29.5	70.0	35.7	91.3	22.14	12.8	54.4	8.3
Phase 2: DRL 18-s schedule											
Small-magnitude (30 μ l) reinforcer											
PkL	17.4	25.5	14.9	17.9	24.3	23.5	18.5	16.5	17.7	20.2	19.3
PkA	0.65	0.25	0.41	0.45	0.41	0.46	0.47	0.47	0.54	0.45	0.47
RF	74.4	79.2	70.8	85.1	96.9	101.4	86.0	59.44	85.7	98.3	88.6
TR	360.3	234.6	219.7	202.6	188.9	184.6	295.4	338.0	272.6	200.0	162.9
PR	207.7	159.4	217.4	181.7	157.4	157.7	184.3	239.1	104.6	172.3	157.7
BR	152.6	75.2	2.3	20.9	31.5	26.9	111.1	98.9	168.0	27.7	5.2
Large-magnitude (300 μ l) reinforcer											
PkL	14.4	16.1	15.3	14.2	16.0	15.7	14.4	15.5	14.6	15.7	16.2
PkA	0.47	0.30	0.36	0.36	0.43	0.42	0.38	0.39	0.44	0.46	0.51
RF	21.1	50.9	43.4	27.7	39.7	38.6	21.7	34.6	29.4	41.6	54.0
TR	493.1	346.0	273.7	346.0	715.4	347.4	692.9	388.8	355.4	496.3	232.6
PR	243.2	220.0	240.3	254.3	184.3	221.4	243.1	220.6	238.3	208.0	213.7
BR	249.9	126.0	33.4	91.7	531.1	126.0	449.8	168.2	117.1	288.3	18.9
Phase 3: Alternating DRL 18-s schedule											
Small-magnitude (30 μ l) reinforcer											
PkL	14.78	17.9	19.09	17.0	21.13	18.0	17.7	17.3	16.3	16.3	21.2
PkA	0.52	0.23	0.38	0.49	0.44	0.50	0.50	0.39	0.52	0.48	0.41
RF	46.8	79.0	84.5	77.0	89.3	90.0	75.3	71.5	62.7	68.8	92.5
TR	346.7	272.3	208.2	225.7	209.5	209.0	274.3	300.5	286.5	338.0	167.5
PR	237.3	191.7	206.2	212.7	186.8	195.8	229.7	239.5	224.7	215.5	160.3
BR	109.4	80.6	2.0	13.0	22.7	13.2	44.6	61.0	61.8	122.5	7.2
Large-magnitude (300 μ l) reinforcer											
PkL	16.8	15.9	15.87	11.7	15.1	14.9	14.9	15.9	13.3	14.2	15.3
PkA	0.32	0.31	0.53	0.44	0.46	0.44	0.43	0.39	0.53	0.45	0.53
RF	60.0	57.3	60.4	21.0	34.5	23.8	24.0	48.0	21.5	27.0	38.3
TR	376.7	339.3	234.0	348.0	373.7	339.0	437.3	310.7	342.7	660.3	260.7
PR	270.7	265.3	230.0	311.2	265.7	285.2	284.7	270.0	274.0	259.5	242.0
BR	106.0	74.0	4.0	36.8	108.0	53.8	152.6	40.7	68.7	400.8	18.7