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VARYING WHEEL-RUNNING REINFORCER DURATION WITHIN A SESSION: EFFECT ON THE REVOLUTION–POSTREINFORCEMENT PAUSE RELATION

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Previous investigations of wheel-running reinforcement that manipulated reinforcer duration across conditions showed a strong relation between wheel-running rate and average postreinforcement pause (PRP) duration. To determine if the basis of this relation across conditions was a local effect of fatigue or satiation, the correlation between revolutions run and the duration of the immediately following PRP was investigated under conditions in which reinforcer duration was either constant or variable within a session. Seven male Wistar rats pressed a lever on a fixed-interval 60-s reinforcement schedule with the opportunity to run for 60 s as the reinforcing consequence. In the constant-duration condition, the duration of the reinforcer was always 60 s. In the variable-duration condition, the duration of the reinforcer varied between 2 and 240 s with a mean of 60 s. Mean correlations between revolutions run and the next PRP duration for constant, variable, and constant conditions were −.07, .20, and −.07, respectively. Although the positive correlation in the variable-duration condition is consistent with an effect of momentary fatigue or satiation, little of the variance in PRP duration appears to be attributable to these factors.

Key words: wheel-running reinforcement, fixed-interval schedule, reinforcer duration, postreinforcement pause, lever press, rats

Belke (1997) showed that local lever-pressing rates decreased and postreinforcement pause (PRP) duration increased as the duration of the opportunity to run as a reinforcing consequence for lever pressing increased. Fatigue and satiation were considered as possible determinants of these relations, but were discounted because wheel-running rates and local lever-pressing rates increased rather than decreased throughout a session, as would be expected if there were cumulative effects of satiation or fatigue. An alternative account considered was that reinforcer duration may influence operant responding through momentary effects of satiation or fatigue. Specifically, after running, an animal would be momentarily fatigued or satiated for running as a reinforcer, and as a result, the probability of pressing a lever for the opportunity to run would be lowest following the termination of a running period. With longer durations, the number of revolutions would be greater and momentary satiation or fatigue would be greater.

Because reinforcer duration in Belke's (1997) study was varied between rather than within conditions, there was insufficient variation in revolutions within a condition to adequately test for local or momentary effects of fatigue or satiation. Consequently, the finding that there was no systematic relation between the number of revolutions run and the duration of the immediately following PRP does not discount the possibility that local satiation or fatigue effects could account for the observed relations between reinforcer duration and operant responding. To assess the potential contribution of local or momentary effects of fatigue or satiation, the relation between revolutions run and the duration of the immediately following PRP was investigated on fixed-interval schedules when reinforcer duration within a session was constant or variable.

METHOD

Subjects

Seven male Wistar rats (Charles River Breeding Laboratories) served as subjects. The animals were approximately 1 year old at the start of the experiment and had previ-

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ously participated in an operant procedure with sucrose solution as a reinforcer. The rats were individually housed in polycarbonate cages (48 cm by 27 cm by 22 cm) in a holding room on a 12:12 hr light/dark cycle (lights on at 8:00 a.m.). Immediately after each experimental session, each subject was given an amount of food sufficient to maintain its weight at approximately 85% of its free-feeding body weight determined when each animal had reached an adult weight of approximately 400 g. Target weights varied between 330 and 340 g. Distilled water was freely available in the home cages.

A second group of 10 male Wistar rats, numbered J1 through J15, was used in a prior study that turned out to be a partial systematic replication of the present study. These rats were maintained under identical conditions.

Apparatus

Subjects were tested in activity wheels (three Wahmann and four Lafayette Instruments Model 86041 A) without side cages. The diameters of the wheels were 35.5 cm. Each wheel was located in a soundproof shell equipped with a fan for ventilation and to mask extraneous noise. A retractable lever (Med Associates ENV-112) was mounted directly at the opening of each wheel. The lever extended 1.8 cm into the wheel chamber through an opening (7 cm by 9 cm) in the center at the base of the wheel frame. The force required to close the lever microswitches ranged between 0.18 and 0.27 N.

A solenoid-operated brake was attached to the base of each wheel. When the solenoid was operated, a rubber tip attached to a metal shaft contacted the outer rim of the wheel and brought the wheel to an immediate stop. A microswitch attached to the wheel frame recorded wheel revolutions. Lights (24-V DC) mounted on the sides of the wheel frame served to illuminate the inside of the wheel chamber. Control of experimental events and recording of data were handled by IBM® personal computers interfaced to the wheels.

Procedure

Fixed-interval schedule access to running. The subjects for this experiment were selected from a group of 21 rats that had been used in a laboratory demonstration in an undergraduate course on basic learning processes. Following the termination of the course, all 21 rats were placed in a running wheel for 30-min sessions each day over a 10-day period. The number of wheel revolutions was recorded for each rat on each day. After 10 days, the rats with the highest running rates were selected for the present study. In the next phase the rats continued to receive 30-min access to the free-moving running wheel. In addition, each rat was placed in an operant conditioning chamber and lever pressing was shaped by the method of reinforcing successively closer approximations. Each lever press produced 0.1 ml of a 15% sucrose solution. When subjects reliably pressed the lever, the schedule of reinforcement was shifted from requiring only a single response per reinforcer (fixed-ratio [FR] 1) to one requiring a variable number of responses averaging three (i.e., a variable-ratio [VR] schedule). This schedule remained in effect for approximately four sessions, with each session terminating when 50 sucrose reinforcers were obtained.

After four sessions on the VR 3 schedule, sessions in the operant conditioning chamber were discontinued. At this point, the retractable lever in each wheel chamber was extended during the wheel-running sessions and the opportunity to run for 60 s was made contingent upon a single lever press. Access to the running period was signaled by the retraction of the lever and the movement of the wheel with the release of the brake. Each session consisted of 30 opportunities to run. The schedule of reinforcement was changed in the following sequence: FR 1, VR 3, VR 5, VR 9, and VR 15. Subjects remained on each

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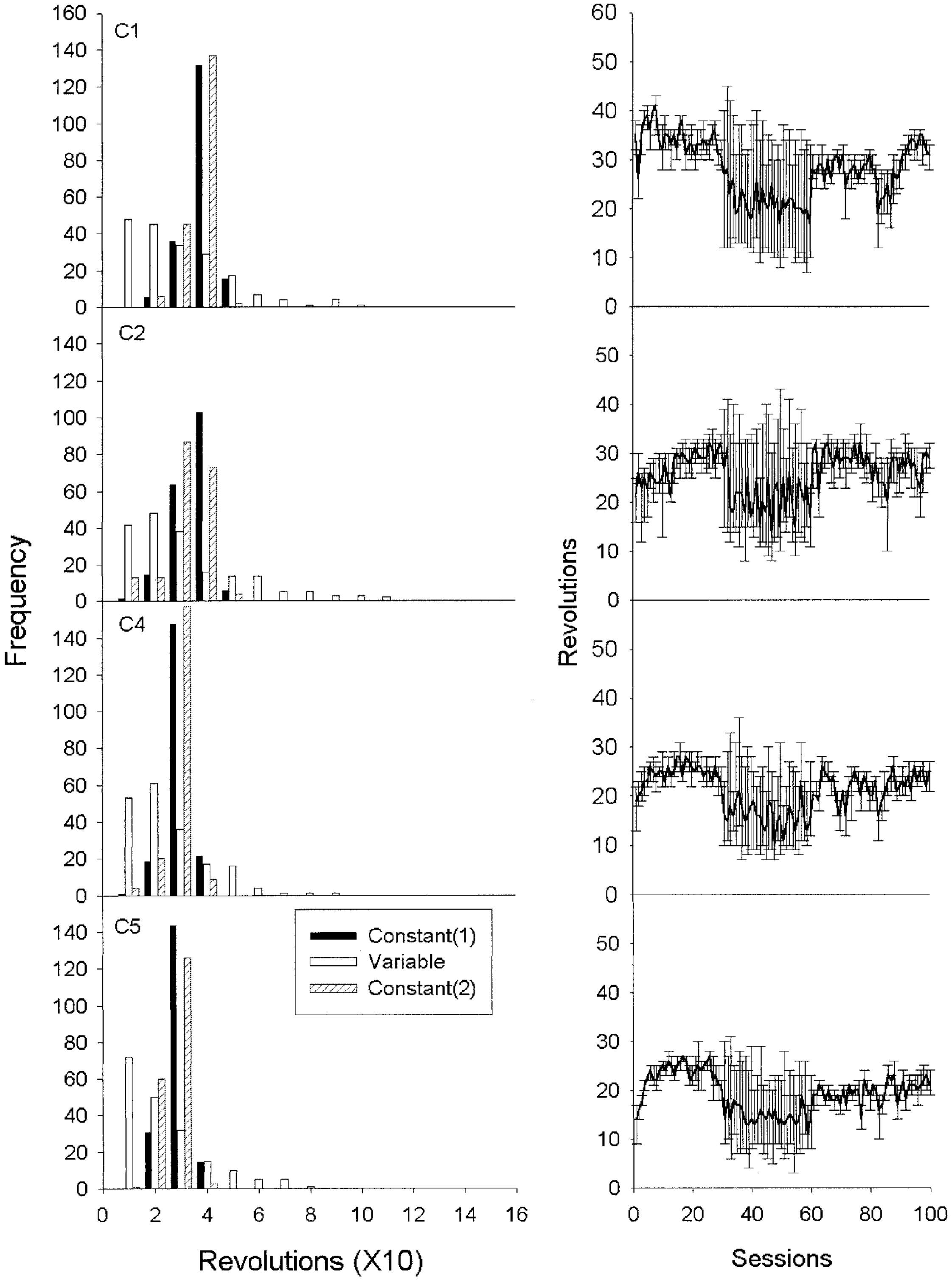
Fig. 1. Frequency distributions for revolutions in the constant and variable reinforcer-duration conditions for Rats C1, C2, C4, and C5 based on data from the final 10 sessions in each condition are displayed in the left panels. The right panels show median and interquartile range revolutions across sessions for these rats. The change from constant to variable reinforcer duration occurred after 30 sessions, and the change from variable back to constant duration occurred after 60 sessions.


C1
C2
C4
C5
Frequency
Revolutions (X10)
0
2
4
6
8
10
12
14
16
0
20
40
60
80
100
120
140
160
Constant(1)
Variable
Constant(2)
Revolutions
Sessions
0
20
40
60
80
100
0
10
20
30
40
50
60

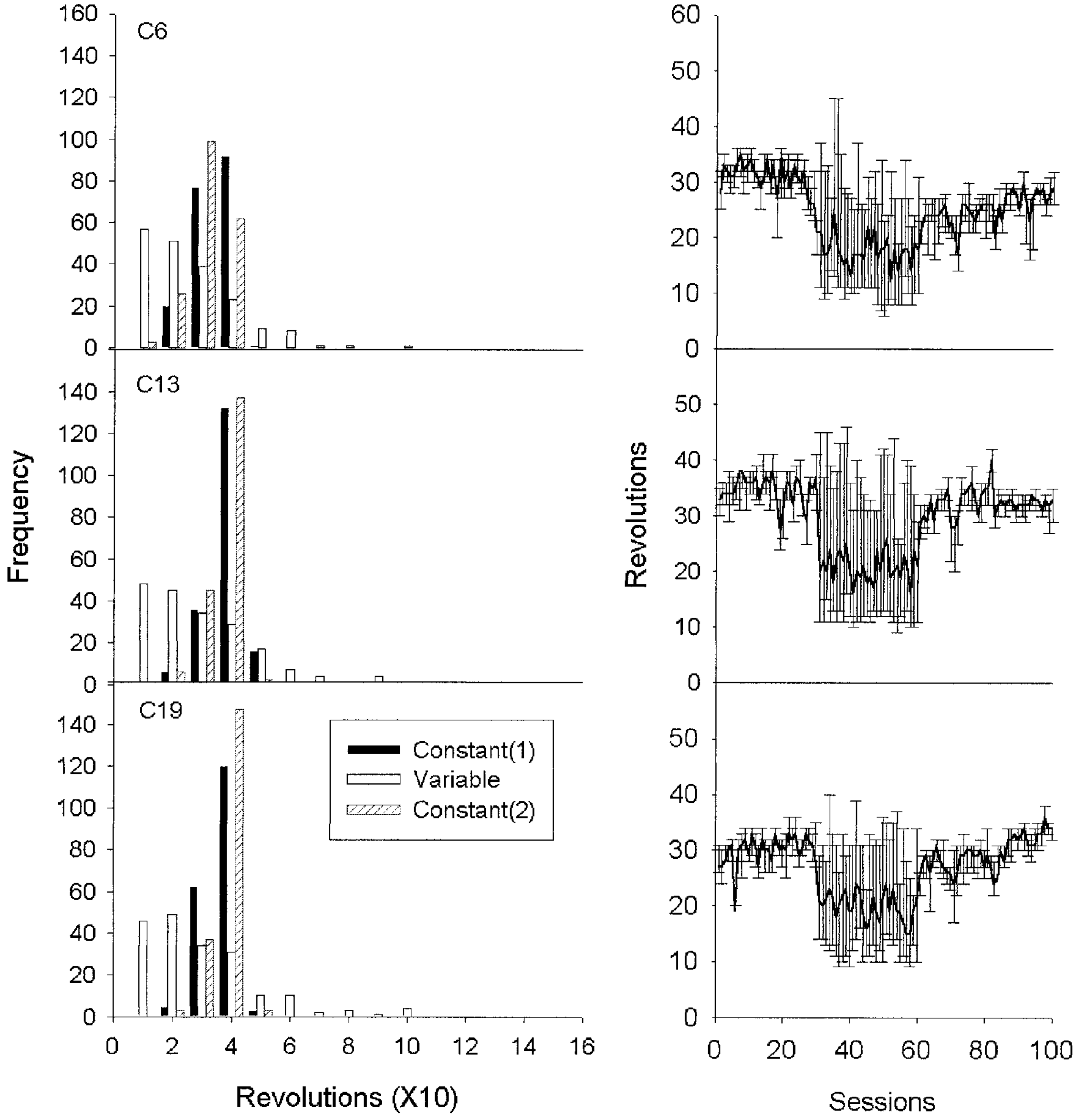


Fig. 2. Frequency distributions for revolutions in the constant and variable reinforcer-duration conditions for Rats C6, C13, and C19 based on data from the final 10 sessions in each condition are displayed in the left panels. The right panels show median and interquartile range revolutions across sessions. The change from constant to variable reinforcer duration occurred after 30 sessions, and the change from variable back to constant duration occurred after 60 sessions.

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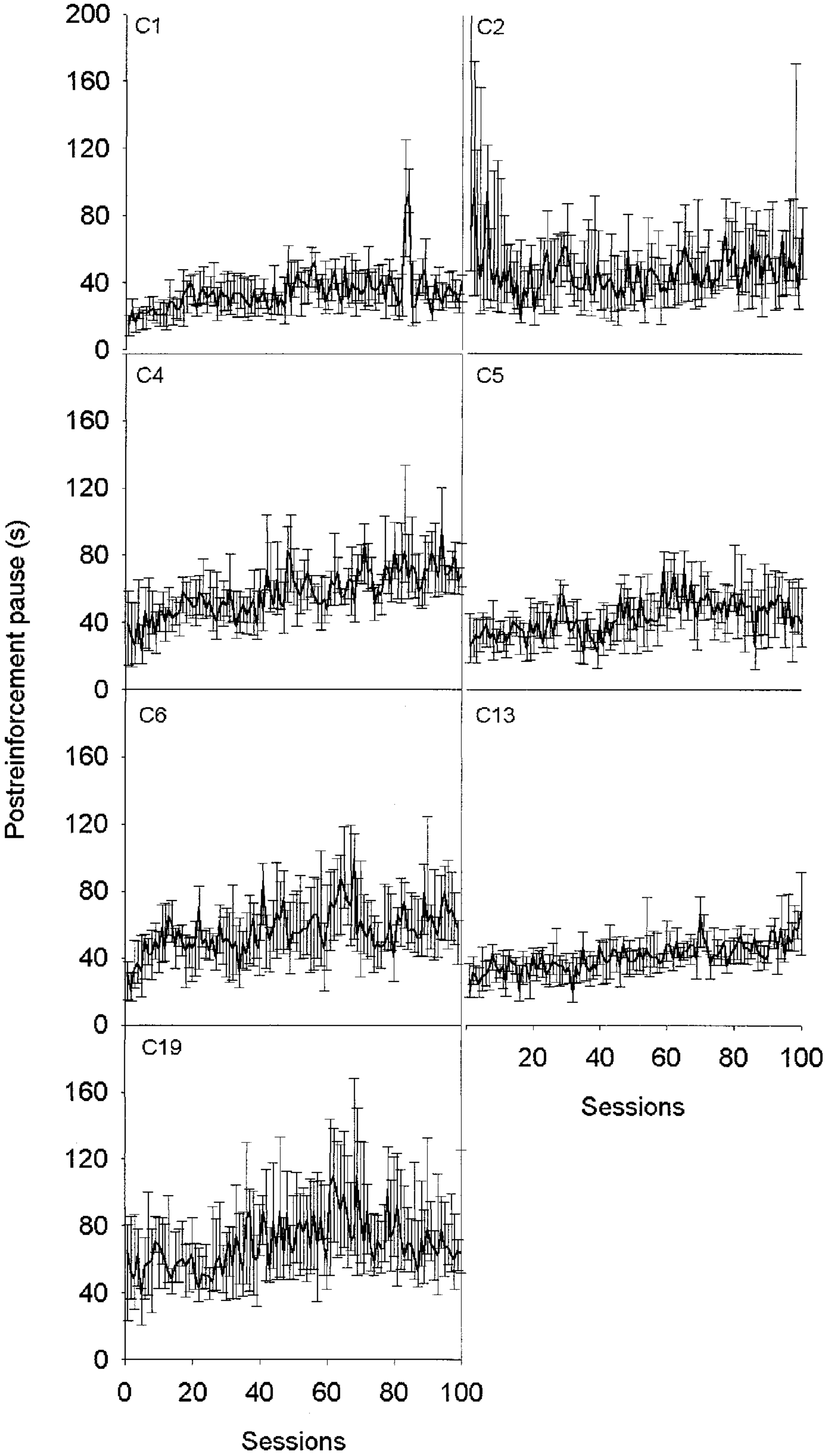
Fig. 3. Median and interquartile range of postreinforcement pauses (in seconds) across sessions for each rat, with changes from constant to variable and variable to constant reinforcer durations occurring at 30 and 60 sessions, respectively.


C1
C2
C4
C5
C6
C13
C19
200
160
120
80
40
0
Postreinforcement pause (s)
0
20
40
60
80
100
Sessions

schedule for four sessions before advancing to the next schedule.

Following training on the VR 15, the rats were placed on a fixed-interval (FI) 60-s schedule of reinforcement. That is, the first lever press that occurred after 60 s since the end of the last running period was reinforced by 60-s access to running. Each session consisted of 20 opportunities to run. These conditions remained in effect for 30 sessions. After 30 sessions, the duration of the opportunity to run was changed to be variable rather than fixed, but had the same mean value; that is, the duration of the opportunity to run could be any one of a number of values ranging from 2 s to 240 s. Intervals for the variable-duration condition were generated using Fleshler and Hoffman's (1962) algorithm for variable-interval (VI) schedule values. The intervals were exponentially distributed, ranged from 2 to 240 s, and had a mean of 60 s. All other conditions remained the same. Following this variable reinforcement-duration condition, a fixed duration of 60 s was reinstated for 30 sessions.

Partial replication with a response-initiated VI schedule. Where appropriate, results from data from the 10 male Wistar rats that were exposed to a similar manipulation prior to the present study will be mentioned. Instead of being exposed to standard FI schedules, these rats responded on a response-initiated VI 30-s schedule with the opportunity to run for 60 s as the reinforcer. On a response-initiated VI schedule, following the termination of the reinforcer, the interval requirement for the next reinforcer does not begin to time until a response is made. The duration of the reinforcer was constant for 30 sessions and then was variable for the subsequent 30 sessions. All other aspects of the procedure were the same as for the group trained with the FI schedule.

RESULTS

The left panels of Figures 1 and 2 display the effect of changing the distribution of reinforcer durations on the frequency distribution of revolutions, and the right panels show the effect of this manipulation on median and interquartile ranges of the distributions of revolutions across sessions. As would be expected, altering the distribution of reinforcer durations directly affected the distribution of revolutions. Changing the distribution of reinforcer durations from a single value to an exponential distribution with the same mean produced a roughly corresponding change in the distribution of revolutions. Frequency distributions changed from distributions dominated by a single value to one with greater spread and suggestive of an exponential form. Across sessions, this change in the distribution of revolutions appears as a decrease in the median number of revolutions and an increase in the interquartile range. Both panels show that these changes varied systematically with the experimental manipulation.

The left half of Table 1 shows that, in addition to changes in the distribution of revolutions, total session revolutions also decreased when reinforcer duration was made variable. All rats, except Rat C2, showed higher running rates in the constant-duration condition than in the variable-duration condition. Rat C2 showed a decline in running with the change from the first constant-duration to the variable-duration condition; however, this change failed to reverse with the second constant-duration condition. For the group, mean wheel-running rates for the first constant-, variable-, and second constant-duration conditions were 29.4, 23.3, and 27.7 revolutions per minute, respectively. With values for the constant-duration condition col-

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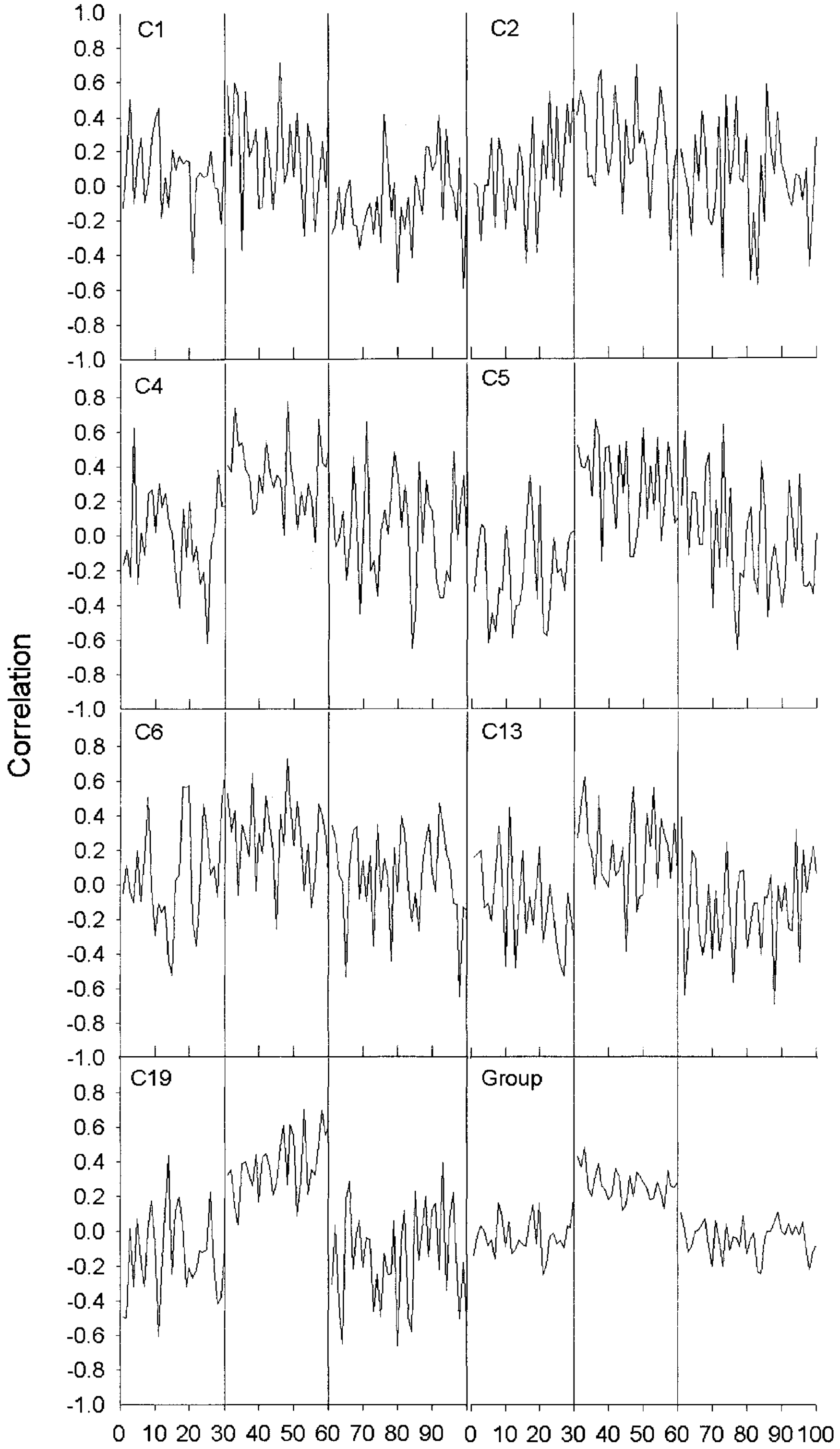
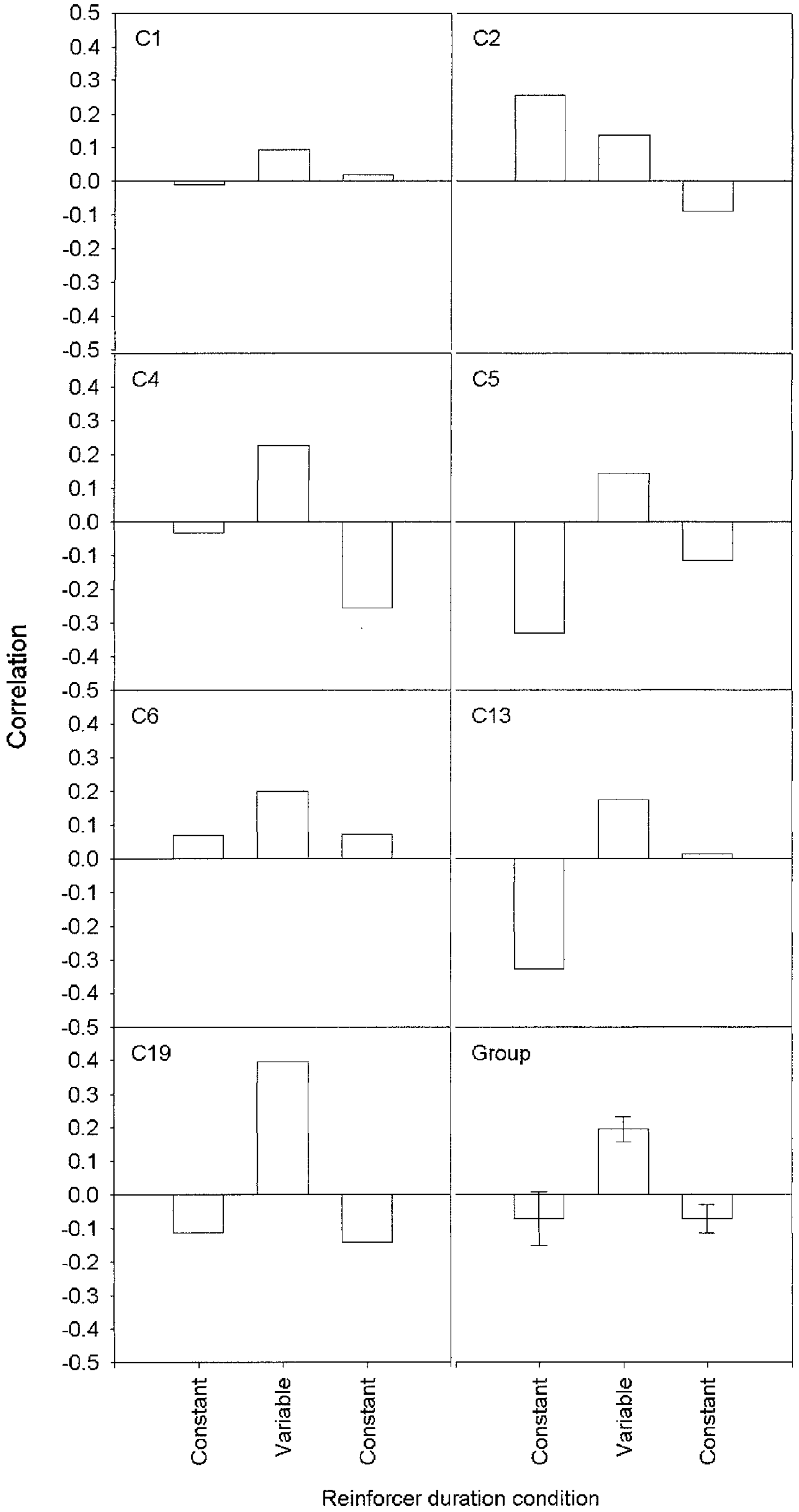
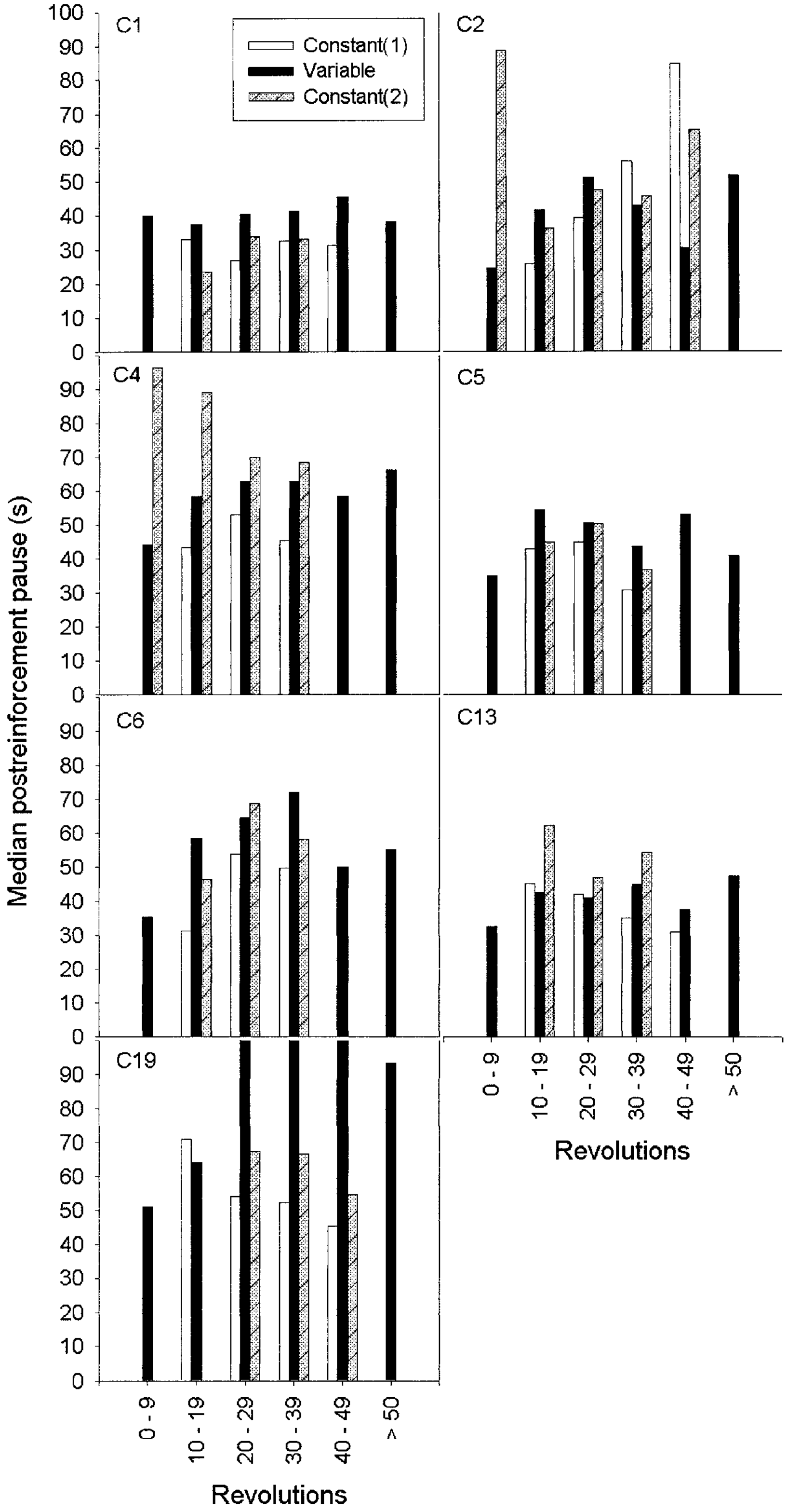
Fig. 4. First-order correlations between revolutions in the previous reinforcement period and duration of the immediately following postreinforcement pause across sessions for each rat and the group. Changes in condition from constant to variable and variable to constant reinforcer durations occurred at 30 and 60 sessions, respectively.

Fig. 5. First-order correlations between revolutions in the previous reinforcement period and the duration of the immediately following postreinforcement pause for data pooled over the last 10 sessions in each reinforcer-duration condition for each rat.

Fig. 6. Median postreinforcement pauses as a function of the number of revolutions in the previous reinforcement period for the constant and variable reinforcer-duration conditions for each rat, based on data pooled over the final 10 sessions in each condition.


Correlation
C1
C2
C4
C5
C6
C13
C19
Group
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
0 10 20 30 40 50 60 70 80 90 0 10 20 30 40 50 60 70 80 90 100


C1
C2
C4
C5
C6
C13
C19
Group
Correlation
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
Constant
Variable
Constant
Constant
Variable
Constant
Reinforcer duration condition


C1
C2
C4
C5
C6
C13
C19
Constant(1)
Variable
Constant(2)
Median postreinforcement pause (s)
0
10
20
30
40
50
60
70
80
90
100
0 - 9
10 - 19
20 - 29
30 - 39
40 - 49
> 50
Revolutions

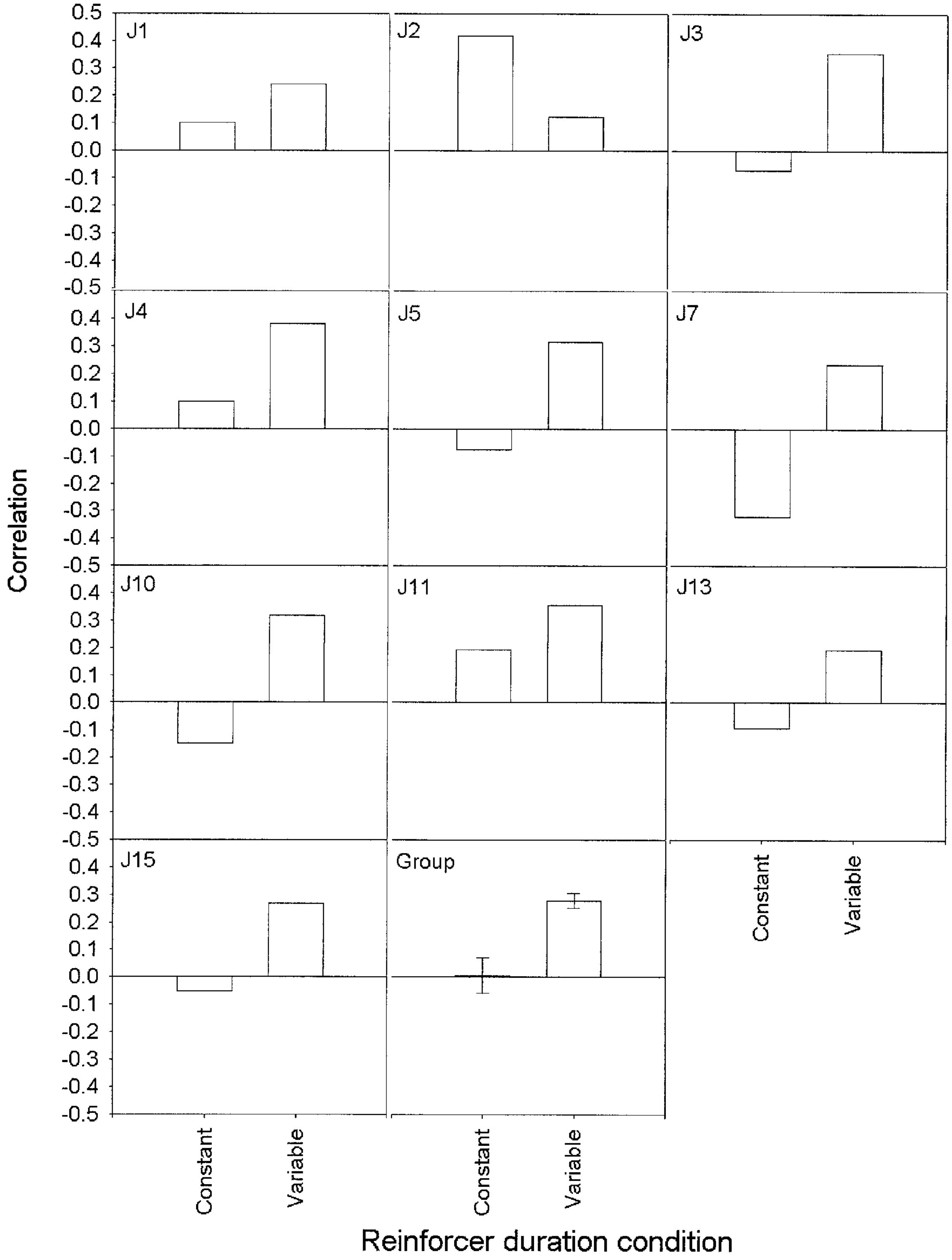


Fig. 7. First-order correlations between revolutions in the previous reinforcement period and the duration of the immediately following postreinforcement pause for the 10 rats that were exposed to constant and variable reinforcer durations while responding on a response-initiated VI 30-s schedule. Correlations are based on revolutions and postreinforcement pauses pooled over the final 10 sessions.

Table 1

Mean wheel-running rates (revolutions per minute) for the constant, variable, and constant reinforcer-duration conditions for each rat in the present study (C series) and for the constant- and variable-duration conditions for the 10 rats that had been previously exposed to this manipulation while responding on a response-initiated variable-interval 30-s schedule (J series). Data are averages from the last 10 sessions in each condition.

Rat	Constant	Variable	Constant	Rat	Constant	Variable
C1	33.5	25.4	31.6	J1	32.6	28.6
C2	28.9	26.7	26.3	J2	28.4	23.7
C4	24.2	19.6	23.2	J3	38.4	35.8
C5	24.6	18.3	21.1	J4	36.1	33.5
C6	30.7	20.7	26.5	J5	22.8	20.1
C13	33.0	28.2	31.5	J7	43.0	33.7
C19	30.8	23.9	32.1	J10	40.5	30.2
M	29.4	23.3	27.7	J11	32.7	31.0
				J13	35.2	29.1
				J15	28.4	28.0
				M	33.8	29.4

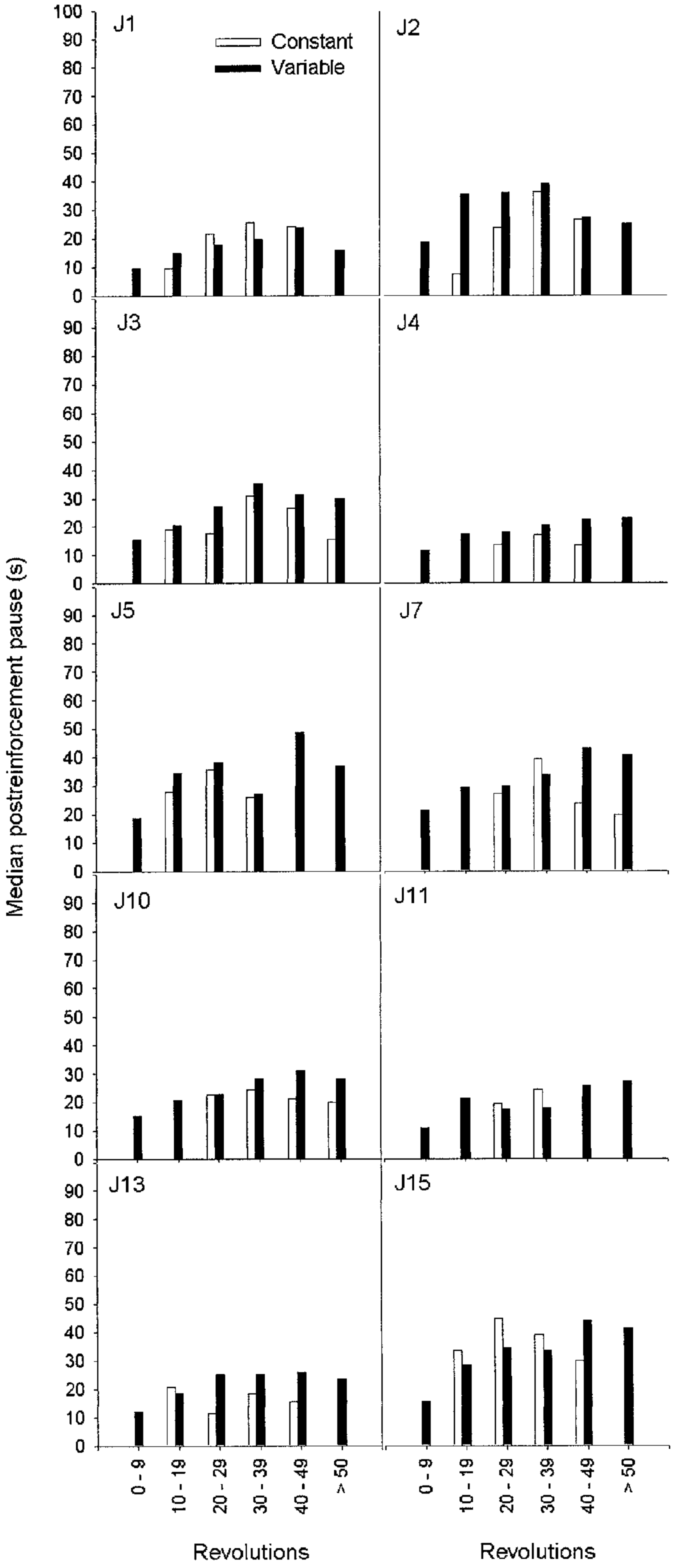
lapsed across the two occurrences of this condition, a paired *t* test comparison confirmed that rats ran at higher rates (i.e., greater number of revolutions per session) when reinforcer duration was constant, $t(6) = 5.43$, $p < .005$.

Figure 3 shows that unlike revolutions, PRPs did not vary systematically with the change in the distribution of reinforcer durations. Neither median PRPs nor interquartile ranges changed systematically across sessions equivalent to those observed in the right panels of Figures 1 and 2. The only change that is apparent in the distribution of PRPs is that for every rat except C2, the median PRP increased across sessions so that the median values in the second constant-duration condition were generally higher than those observed during the initial constant-duration condition.

Figure 4 shows the correlation between the revolutions run during a reinforcement period and the duration of the immediately following PRP for each session across the constant- and variable-duration conditions. This graph shows that although there was considerable day-to-day variability, in general, correlations varied systematically with the manipulation. Correlations were systematically higher in the variable-duration condition. Averaging across individuals to produce the group function reduces some of the nonsystematic variance and clearly shows how the revolution–pause duration correlations changed with the manipulation.

Figure 5 shows the same correlations obtained for the constant and variable conditions based on the revolutions and immediately following PRPs pooled over the last 10 sessions of each condition. This graph shows that when the reinforcer duration was constant, no systematic relation occurred between revolutions and PRP duration. However, when reinforcer duration was varied, for all rats there was a positive correlation between revolutions run and the subsequent PRP duration. Mean correlations for the constant-, variable-, and constant-duration conditions were −.07, .20, and −.07, respectively. Paired *t* tests showed that only the variable-duration condition produced correlations significantly different than zero, $t(6) = 5.24$, $p < .005$.

Figure 6 shows median PRP durations as a function of the number of revolutions in the preceding reinforcement period for the constant and variable reinforcer-duration conditions for each rat. Revolutions and subsequent PRPs were pooled across the last 10 sessions in each condition and sorted by number of revolutions. In the constant-duration conditions there was no systematic relation between number of revolutions run and the duration of the immediately following PRP. For example, in the first constant-duration condition, Rats C2 and C6 showed a positive relation between revolutions run and median PRP, Rats C13 and C19 showed a negative relation, and Rats C1, C4, and C5 showed no systematic or linear relation. In the variable-duration condition, with the exception of Rat C1 all animals showed lower median PRPs when nine or fewer revolutions were run. Beyond this, no systematic relation appears between revolutions run and the duration of the immediately following pause. Average median PRPs for 0–9, 10–19, 20–29, 30–39, 40–49, and >50 revolutions were 37.51, 50.98, 59.76, 58.30, 53.56, and 56.07 s, respectively. A repeated measures analysis of variance (ANOVA) revealed a significant effect of revolutions on pausing, $F(5, 30) = 5.45$, $p < .01$. However, Dunnett *t* test comparisons showed that the only significant differences between categories of revolutions were between 0–9 revolutions and all other


J1
J2
J3
J4
J5
J7
J10
J11
J13
J15
Constant
Variable
Median postreinforcement pause (s)
0
10
20
30
40
50
60
70
80
90
100
0 - 9
10 - 19
20 - 29
30 - 39
40 - 49
> 50
Revolutions
Revolutions

categories. Thus, the effect of revolutions on subsequent PRPs appears to be limited to shorter pauses following a small number of revolutions.

Partial replication with the response-initiated VI schedule. Similar analyses were performed on the data pooled over the last 10 sessions from rats that were exposed to the response-initiated VI schedule. As might be expected based on the difference in type and duration of reinforcement schedule, the durations of PRPs were lower on the response-initiated VI schedule. For the constant- and variable-duration conditions, average median PRPs were 24.94 and 23.67 s, respectively. For rats on the FI schedule, equivalent values for the constant-, variable-, and constant-duration conditions were 44.35, 50.94, and 54.85 s, respectively.

The right half of Table 1 shows that, as was the case for the rats on the FI schedule, wheel-running rates decreased when the duration of the opportunity to run was made variable. All rats ran at higher rates when reinforcer duration was constant. For the group, mean wheel-running rates for the constant- and variable-duration conditions were 33.81 and 29.36 revolutions per minute, respectively. A paired t test comparison confirmed that wheel-running rates were higher when the duration was constant, $t(9) = 4.32$, $p < .005$.

Figure 7 shows correlations between revolutions and subsequent pauses pooled over the last 10 sessions in the constant- and variable-duration conditions for the rats that had responded on a response-initiated VI schedule. As was the case with the FI schedule, correlations in the constant-duration condition were not systematic. Correlations ranged from .42 to $-.32$, with a mean value of .01. In the variable-duration condition, all animals showed positive correlations that ranged from .12 to .38, with a mean of .28. Paired t tests once again showed that only the variable-duration condition produced correlations significantly different than zero, $t(9) = 10.83$, $p < .001$.

Analysis of median PRPs as a function of revolutions run in the preceding reinforcement period for these rats (Figure 8) produced results similar to those observed for the FI schedule. Average median PRPs for 0–9, 10–19, 20–29, 30–39, 40–49, and >50 revolutions were 14.91, 24.04, 26.64, 28.01, 32.25, and 29.10 s, respectively. A repeated measures ANOVA revealed a significant effect of revolutions on pausing, $F(5, 45) = 19.19$, $p < .0001$. Dunnett t test comparisons showed that median PRPs for 0–9 revolutions were significantly lower than median PRPs for all other categories of revolutions.

DISCUSSION

The present study showed that when reinforcer duration was changed from a single value to an exponential distribution of values with the same mean, all animals showed a positive relation between revolutions run and the duration of the immediately following PRP. This result suggests a local effect of running on PRP duration that is consistent with a local or momentary effect of fatigue or satiation. However, the correlations were modest and the amount of variance in PRP duration accounted for by variation in revolutions was small—about 4% on average. Further analysis suggested that the source of this positive covariance appeared to be shorter PRPs following small numbers of revolutions, with no systematic relation over most of the range of revolutions.

The lack of systematic variance over most of the range of revolutions generated would also account for the absence of a relation between revolutions and PRPs in the constant-duration condition. In that condition, there would be insufficient variation in revolutions to reveal the relation that became apparent when reinforcer duration was varied.

Replication of these findings in the rats ex-

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Fig. 8. Median postreinforcement pauses as a function of the number of revolutions in the previous reinforcement period for the constant and variable reinforcer-duration conditions for the 10 rats that were exposed to constant and variable reinforcer durations while responding on a response-initiated VI 30-s schedule, based on data pooled over the final 10 sessions in each condition.

posed to the equivalent manipulation on a response-initiated VI rather than an FI schedule further substantiates that the relation between revolutions run and pause duration is weak. On the response-initiated VI schedule, the contribution of the schedule to pause duration should have been less due to both the smaller schedule value and the aperiodicity of the schedule. Consequently, the contribution of factors related to revolutions run, such as fatigue or satiation, should have been more apparent under these conditions. As expected, pause duration was shorter; however, the variance in pause duration accounted for by revolutions did not change substantively.

The weak relation between revolutions and pause duration in the present study stands in contrast to the stronger relations observed in studies using food reinforcement (Hatten & Shull, 1983; Lowe, Davey, & Harzem, 1974; Staddon, 1970). For example, Staddon found that PRP duration on FI schedules varied systematically with reinforcer duration in pigeons when food hopper duration was randomly varied from reinforcer to reinforcer within a session over five durations ranging from 1.3 to 9.0 s. Lowe et al. observed a similar systematic relation between sucrose concentration and PRP duration on FI schedules with sucrose concentration varying between 10% and 70% within a session. In their study, different concentrations were presented in blocks of six reinforcements, with the order of blocks randomized across sessions.

One difference between the present study and those using food reinforcement that may account for the difference in the strength of the observed relation between reinforcer and PRP durations is the number of reinforcer durations and magnitudes. In the present study, there were 20 reinforcer durations exponentially distributed between the lowest (2 s) and the highest (240 s) value. In the food reinforcement studies, the number of different values ranged between two and five. Thus, in the food reinforcement studies, differences between values were probably, on average, greater than those in the present study. As a result, differences in inhibitory aftereffects associated with different values may have developed more clearly. The greater number of values in the present study may have worked in combination with varying the duration from reinforcer to reinforcer to diminish the likelihood that a strong relation between revolutions run and PRP duration would develop. A stronger relation might result if fewer reinforcer durations were varied across blocks of reinforcers rather than individual reinforcers.

There may be reason to suspect that the relation between reinforcer duration and PRP duration may not be linear. As reinforcer duration increases, the number of revolutions run increases, but the rate of running decreases (Belke, 1997; Belke & Dunbar, 1998). The decline in rate may reflect an increase in the likelihood of pausing during the reinforcement period. Presumably, pausing during the reinforcement period would serve to lessen the effect of fatigue on the duration of the subsequent PRP. Thus, although total revolutions may increase as reinforcer duration increases, the effect of this increase on PRP duration may be mitigated by the decline in rate. Consequently, as observed, PRP duration might be expected to increase and then level off or even decrease as revolutions increase.

At the session level, the decline in revolutions when reinforcer duration was variable is likely an effect of the unpredictability of the reinforcer duration on running during the reinforcement period. When the reinforcement period is constant, running during the period displays a cumulative pattern opposite that observed for responding on an FI schedule. That is, wheel-running rates tend to be highest at the beginning of the reinforcement period and decline as the reinforcement period elapses. Assuming that this pattern manifests a temporal discrimination, varying the reinforcer period, particularly when intervals range widely between very short and very long values, is likely to disrupt this pattern with a resultant decline in revolutions. Interestingly, the effect of the unpredictability of the reinforcer period on the consequential behavior is opposite the effect of unpredictability of the reinforcement requirement on operant responding.

In sum, the present study demonstrated a positive relation between revolutions run and PRP duration, which suggests that there are local effects of fatigue or satiation associated with wheel-running reinforcement. However, the observed relation was not strong enough to conclude that longer PRP durations observed with wheel-running reinforcement are largely due to these local effects, nor do they appear to account for the relation between reinforcer and PRP duration observed between conditions using different reinforcer durations (Belke, 1997; Belke & Dunbar, 1998).

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