TEMPORAL CONTROL BY SIGNALS OF INTERVAL DURATION WITHIN VARIABLE-INTERVAL SCHEDULES

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Rats' lever pressing produced sucrose reinforcers on a variable-interval schedule where, in different conditions, the duration of a stimulus presented immediately after reinforcement was either correlated or uncorrelated with the duration of the current interreinforcement interval. Under the baseline schedule, in which no stimulus was presented, the minimum interreinforcement interval was 8 s and the mean postreinforcement pause of each subject approximated this value. Response rates increased slowly over the first 10 to 15 s and then remained roughly constant throughout the remainder of the interval. In both the correlated and uncorrelated conditions, the added stimulus resulted in the postreinforcement pauses lengthening to values in excess of the duration of the preceding stimulus. This resulted in a poststimulus pause which was, in most cases, roughly constant irrespective of the duration of the preceding stimulus, or of the reinforcement contingencies prevailing immediately after stimulus offset. Local response-rate patterns in the uncorrelated conditions were similar to those obtained under the baseline schedule in which no stimulus was presented. However, in the correlated condition local response rates increased across the remainder of the interreinforcer interval. Further, the rate of acceleration was inversely related to the duration of the preceding stimulus. These results show that a correlation between stimulus duration and the ensuing time to reinforcement can control behavior—a type of temporal control not previously reported.

Key words: temporal control, inhibitory stimulus control, variable-interval schedules, lever press, rats

Fixed-interval (FI) responding is typified by a pause after reinforcement followed by an acceleration in response rate towards a high terminal rate (Ferster & Skinner, 1957, chap. 5). This pattern of responding has often been taken as evidence for temporal control by the schedule (e.g., Staddon, 1972) or timing by the subject (Church, 1978), rather than as a result of nontemporal factors such as the aftereffects of reinforcement. This view is supported by findings that the postreinforcement pause (PRP) duration is strongly related to the FI value.

Further evidence of temporal control comes from studies in which initially neutral stimuli have been added to an FI schedule.

For example, Dews (1966) found that when an S^A was present throughout an FI of 500 s except during the 50-s terminal segment (S^D) and one earlier 50-s segment, the rate of responding during the probe S^D depended mainly on the time during the interval at which the probe occurred. Similar effects have been reported also by Farmer and Schoenfeld (1966) who inserted an "added stimulus" into an FI 60-s schedule. The effects of the stimulus depended upon its location within the interreinforcer interval. When it occurred in close proximity to the next reinforcer, the stimulus increased responding, but it suppressed responding when presented earlier in the interval.

Within an FI schedule an added stimulus that occurs regularly at a particular time signals both the time since the last reinforcer and the time until the next one. It may therefore be unclear which of these properties is responsible for the behavioral effects. Within a variable-interval (VI) schedule,

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however, these two properties could be separated. An added stimulus might occur a fixed period before reinforcement, for example. In a version of this procedure, Stubbs (1971) exposed pigeons to VI schedules within which a response-produced brief stimulus occurred on an FI schedule. The occurrence of the brief stimulus signaled that the next reinforcer would not occur until the expiry of the next FI at the earliest. Under these conditions both paired and unpaired brief stimuli generated typical FI patterns of responding. Van Haaren and Krafft (1982) introduced an added stimulus to a VI schedule that was not response-produced. However, in their study the added stimulus was presented with respect to the previous reinforcer as well as to the next one. Specifically, a visual or auditory stimulus, equal in duration to one tenth of the prevailing interreinforcement interval, was presented either "early" (after 20% of the interval had elapsed) or "late" (after 80% of the interval had elapsed). The effects of the auditory stimulus were inconsistent, but when the visual stimulus was presented early, it reduced response rate considerably relative to its effects when presented late. Thus the authors concluded that "the intrusion of a stimulus on a VI baseline and its relation to reinforcement presentation can have 'Pavlovian conditioning like' effects" (p. 232). Also, as an increase in response rate was observed after termination of a late stimulus, they suggested that "stimulus termination also served as a discriminative stimulus" (p. 233).

Of particular interest here is the relationship that Van Haaren and Krafft created between the duration of the added stimulus and the interval of time separating stimulus offset and the presentation of the next reinforcer. Because stimulus duration was always equal to one tenth of the prevailing interval and was always presented after two tenths of the interval had elapsed, stimulus duration was perfectly correlated with the stimulus offset—reinforcer interval. For example, in an interval in which stimulus duration was 10 s, the stimulus offset—reinforcer interval would be 70 s. Alternatively,

if stimulus duration was 1 s, the latter duration would be 7 s. In general, then, a relatively short stimulus duration would signal a relatively short stimulus offset—reinforcer interval and a relatively long duration would signal a relatively long interval. The same argument would apply in the condition in which the stimulus was presented late in the interreinforcer interval. It is not possible to determine from Van Haaren and Krafft's results whether or not this accidental relationship was a potential source of behavioral control.

The present experiment directly investigated this possibility that a correlation between the duration of an added stimulus and the stimulus offset—reinforcer interval may control responding within a VI schedule. In different conditions, the duration of a stimulus that was presented immediately after reinforcement was either correlated or uncorrelated with the time at which the next reinforcer became available. Given that responses would never be reinforced during the stimulus, we might predict that responding would not occur in its presence. However, if a short stimulus predicted a short stimulus offset—reinforcer interval, and a long stimulus predicted a long stimulus offset—reinforcer interval, would this relation influence the rate or pattern of responding?

METHOD

Subjects

Seven experimentally naive male hooded rats, approximately six months old at the start of the experiment, were maintained at 80% of their free-feeding weights and were caged singly with water always available.

Apparatus

Two Campden Instrument test chambers (Model 410) fitted with dipper feeders were used. Two levers protruded from one wall of each chamber, 6 cm above the grid floor and 10.5 cm apart. Only the left lever was operative, requiring a force of approximately 0.1 N to register a lever press. A 2.8-W stimulus

light was situated 4 cm above each lever and a third stimulus light was situated 15 cm above the grid floor equidistant from the two levers. During experimental sessions the test chamber was illuminated by a 2.8-W house-light located in the center of the chamber ceiling. Each test chamber was 24 cm long, 22 cm wide, and 20 cm high. A 6 cm, 35-Ohm, 1-W loudspeaker, which could deliver a tone into the test chamber, was located on the chamber ceiling adjacent to the houselight. In this study a 600-Hz, 92-dB tone was used. The reinforcer was 3-s access to 5% sucrose solution (by weight), delivered by a motor-driven dipper into an aperture in the floor of a recessed tray situated at floor level between the two levers. A hinged, clear plastic flap covered the food tray and the reinforcer was timed when this flap was opened by the rat. During reinforcement availability the food tray was lit by a 2.8-W light. Each test chamber was encased in a sound-attenuating housing that was fitted with a ventilating fan. A Data General Nova 2/10 minicomputer programmed in ACT (Millenson, 1975) controlled the experiment and collected data.

Procedure

Each rat received one daily session (Monday through Saturday) that terminated when

100 reinforcers had been obtained. After lever pressing was hand shaped with sucrose reinforcers, each rat was exposed to four sessions during which every lever press was reinforced before being transferred to a series of schedules each of which generated interreinforcer intervals of variable duration but with an average of 28 s. Table 1 gives for each subject the sequence of conditions, brief details of the schedules, and the number of sessions in each condition. Rats remained in a condition until lever pressing showed no systematic change over five consecutive sessions and the mean PRP varied by less than 10% of the total mean PRP of those five sessions.

Condition 1: Baseline VI training. No stimulus was presented. In each interreinforcer interval, a fixed-time (FT) 6-s component was followed by a random-time (RT) 11-s component. The probability that this component would terminate after each successive second was .09. On termination it was followed by a random-interval (RI) 11-s component in which the probability was .09 that a reinforcer would be made available after each second. The schedule was thus VI 28-s with a minimum interreinforcer interval of 8 s. Here, and in all subsequent conditions, once a reinforcer became available, no further reinforcers could be scheduled until

Table 1
Sequence of conditions, schedule parameters, and the number of sessions in each condition for each subject.

Sequence of conditions	Interreinforcer interval (s)		Stimulus duration (s)		R3	R4	R5	R6	R7	R8	R9
	minimum	mean	minimum	mean							
1 No stimulus	8	28	—	—	46	46	45	41	44	42	45
2 Fixed-duration stimulus (6 s)	8	28	6	6	39	44	44	43	39	39	36
1 No stimulus	8	28	—	—	10	10	10	10	10	10	10
3 Variable-duration stimulus (mean 17 s)	8	28	7	17		33		33	35		31
4 Variable-duration stimulus (mean 14 s)	14	28	7	14	35		35			33	
2 Fixed-duration stimulus (6 s)	8	28	6	6	10	10	10	10	10	10	10
5 Correlated variable-duration stimulus (mean 14 s)	14	28	7	14	42	42	46	43	39	44	40

that reinforcer was obtained. With an RI schedule the conditional probability of a reinforcer being made available (the theoretical reinforcements/opportunity function) does not change with time since reinforcement. With the schedule used here, however, the conditional probability slowly increases with time since reinforcement.

Condition 2: Fixed-duration stimulus. Here, and in all the conditions described subsequently, a stimulus occurred in the first part of each interreinforcer interval. This consisted of the three stimulus lights flashing at 2.5 Hz (on time = off time) and the 600 Hz tone. Each reinforcer was made available following the FT, RT, RI sequence used in Condition 1, but the stimulus was presented in the 6-s FT component.

Condition 3: Variable-duration stimulus (mean 17 s). The duration of the stimulus was extended to include the FT and RT components. Otherwise the schedule remained the same as in Condition 1.

Condition 4: Variable-duration stimulus (mean 14 s). The stimulus occurred during the FT and RT components, but the latter was now RT 8-s; that is, the probability that this component terminated after each successive second was .125. To keep the same mean interreinforcer interval, the final component, in which the stimulus was not present, was changed to RI 14-s. The probability was .5 that a reinforcer would be made available after each 7 s.

Condition 5: Correlated variable-duration stimulus. The stimulus occurred during successive FT 6-s and RT 8-s components, as in Condition 4, but the remainder of the interreinforcer interval was set equal to the stimulus duration obtained on that occasion. Thus if the stimulus was presented for 9 s, then a reinforcer would be made available after a further 9 s.

The range of schedules in Conditions 1 to 5 permitted a number of comparisons to be made while reinforcement rate (mean interreinforcer interval) was held constant. Condition 1 provided a VI schedule with a relatively short minimum interreinforcer interval. Condition 2 was the same, except that a

stimulus was presented within that minimum interreinforcer interval. Thus the effect of simply presenting a stimulus at the beginning of an interreinforcer interval can be assessed by comparing responding in Conditions 1 and 2. In Condition 3 the schedule of interreinforcer intervals was again the same but the stimulus signaled a longer varying time in which a reinforcer could not be obtained. Condition 4 resembled Condition 3, except that the average stimulus duration was shorter and equal to half the mean interreinforcer interval. Thus in Conditions 2, 3, and 4 the stimulus offset was uncorrelated with the duration of the remainder of the current interreinforcer interval. Condition 5 was similar to Condition 4, except that each stimulus duration was identical with the remainder of the current interreinforcer interval.

RESULTS

In all conditions, more than 90% of the interreinforcer intervals were of 44-s duration or less. Consequently, the range 0 to 44 s was used in all conditions for data analysis.

Patterns of responding under baseline VI training (Condition 1), during which there was no added stimulus and during which there was a fixed-duration 6-s stimulus (Condition 2), are shown in Figure 1 based on the last five sessions in each condition. Throughout the experiment responses were recorded second-by-second, and the data shown are local response rates as a function of time since reinforcement. As interreinforcer intervals varied in duration, the local response rate was calculated as the number of responses occurring in the n th second following reinforcement divided by the number of interreinforcer intervals in the distribution of n s or longer (cf. Leslie, 1981). The local response-rate curves were based on 100 observations at 0 s, declining to approximately 30 observations per session at 32 s. Under the baseline VI schedule, local response rates increased slowly over the first 10 to 15 s and then remained roughly constant. The introduction of a 6-s stimulus

had no systematic effect. For any schedule, a reinforcements/opportunity function can be calculated. This gives the conditional probability of a reinforcer being made available at any time since the last reinforcement (cf. Leslie, 1981). The reinforcements/opportunity function with the VI schedules used in Conditions 1, 2, and 3 had a value of zero up to 8 s and then increased slowly in a negatively accelerating fashion. However, as Figure 1 shows, local response rates under Conditions 1 and 2 did not generally show a corresponding increase beyond 16 s. The local rates of one subject, R4, were an exception to this generalization.

Fig. 1. Local rates of responding as a function of time since reinforcement when no stimulus was presented (solid lines, Condition 1) and when a 6-s stimulus followed reinforcement (dashed lines, Condition 2).

The similarity of performance under the baseline VI schedule and when the fixed-duration 6-s stimulus was added was confirmed by data on postreinforcement pauses. Across animals, mean PRPs ranged between 7.1 and 11.6 s in Condition 1 and between 7.6 and 13.8 s in Condition 2. When the rats were later returned to these conditions (see Table 1), the ranges were 7.3 to 12.6 s and 8.5 to 12.6 s, respectively.

When exposed to schedules with a varying duration stimulus uncorrelated with the interreinforcer interval (Condition 3 or 4), all rats developed the same pattern of respond-

ing. Responding was absent during the stimulus, began within a few seconds of stimulus offset, and then gradually increased before reaching a steady rate later in the interreinforcer interval. Figure 2 shows the intervals between stimulus offset and the first response as a function of the duration of the immediately preceding stimulus. This post-stimulus pause was roughly constant in five cases, increased in R7, and decreased in R3.

As it was possible that the pattern of responding would vary as a function of the duration of the stimulus presented in that particular interval, Figures 3 and 4 give local rate of responding as a function of the time since reinforcement and the duration of the stimulus. They are thus similar to Figure 1 but with a third dimension added. Note that in both figures responding was entirely absent during stimulus presentations. Otherwise, there was some variability but no systematic differences between animals or conditions. The poststimulus pauses and the subsequent local response-rate patterns in Conditions 3 and 4 were similar, despite the fact that the minimum stimulus offset—reinforcer interval was 1 s in Condition 3 and 7 s in Condition 4.

Table 2 provides quantification of the data presented graphically in Figures 3 and 4. Linear regression equations were calculated between the time since stimulus offset and the local response rate following each range of stimulus durations. The number of observations varied from 17 to 11 as stimulus duration increased. The upper portion of Table 2 shows that the slopes of these regression lines are close to zero and the associated correlation coefficients are low. This indicates that local response rates were roughly constant over time.

With a correlated variable-duration stimulus (Condition 5) there was a perfect positive correlation between stimulus duration and interreinforcer interval. Figure 2 shows that poststimulus pauses were again unrelated to stimulus duration, but following the onset of responding, a different response pattern occurred for some animals. Figure 5, which gives local response rates in

Fig. 2. Poststimulus pauses following stimuli of various durations when duration was uncorrelated (unfilled circles, Condition 3 or 4) or correlated with the interreinforcer interval (filled circles, Condition 5).

this condition as a function of both time since reinforcement and the preceding stimulus duration, shows that response rate generally increased throughout the stimulus offset—reinforcer interval. Furthermore, the rate of increase was a function of stimulus duration. Response rate increased most rap-

idly in the shortest stimulus offset—reinforcer interval, and least rapidly in the longest ones. Terminal response rate, that occurring just before reinforcement, was thus not systematically related to the time spent responding in that interval.

The information of Figure 5 can again be

Fig. 3. Local rates of responding in Condition 3 as a function of time since reinforcement and preceding stimulus duration.

Fig. 4. Local rates of responding in Condition 4 as a function of time since reinforcement and preceding stimulus duration.

confirmed by reference to the bottom half of Table 2. This gives the slope and associated correlation coefficients of linear regression

equations calculated between time since stimulus offset and local response rate. The number of observations varied between 4

Table 2
Correlation coefficients (*r*) and slopes (*s*) of linear regressions between time since stimulus offset (in 2-s intervals) and local response rates.

Stimulus duration (s)	Condition 3								Condition 4							
	R4		R6		R7		R9		R3		R5		R8			
	<i>r</i>	<i>s</i>	<i>r</i>	<i>s</i>	<i>r</i>	<i>s</i>	<i>r</i>	<i>s</i>	<i>r</i>	<i>s</i>	<i>r</i>	<i>s</i>	<i>r</i>	<i>s</i>	<i>r</i>	<i>s</i>
7- 9.9	0.52	0.08	0.34	0.02	0.57	0.05	0.31	0.01	-0.58	-0.06	0.48	0.03	0.36	0.04		
10-12.9	-0.22	-0.03	0.22	0.01	0.26	0.02	-0.27	-0.02	-0.11	-0.01	0.54	0.04	0.40	0.06		
13-15.9	0.55	0.07	0.71	0.06	-0.21	-0.01	0.24	0.02	-0.75	-0.10	-0.39	-0.04	0.14	0.02		
16-18.9	0.56	0.09	0.71	0.07	0.59	0.06	0.35	0.03	-0.26	-0.03	0.30	0.03	0.30	0.04		
19-21.9	0.57	0.10	0.49	0.04	0.59	0.05	0.66	0.07	-0.86	-0.14	0.59	0.05	0.59	0.15		
Condition 5																
7- 8.9	1.00	0.96	1.00	0.47	0.99	0.49	0.97	0.73	0.99	1.00	0.99	0.24	0.91	0.92		
9-10.9	0.99	0.81	0.99	0.38	1.00	0.44	0.99	0.59	0.98	0.88	0.99	0.27	0.91	0.72		
11-12.9	0.99	0.59	0.99	0.30	1.00	0.44	0.99	0.54	0.98	0.74	0.96	0.22	0.94	0.67		
13-14.9	0.96	0.49	0.97	0.30	0.99	0.39	0.99	0.47	0.93	0.54	1.00	0.19	0.95	0.63		
15-16.9	0.88	0.33	0.97	0.21	0.99	0.34	0.99	0.33	0.92	0.50	0.95	0.17	0.96	0.51		
17-18.9	0.79	0.30	0.95	0.25	0.99	0.34	0.97	0.32	0.94	0.36	0.97	0.12	0.96	0.48		
19-20.9	0.86	0.28	0.94	0.19	0.99	0.25	0.99	0.29	0.98	0.35	0.88	0.08	0.93	0.37		
21-22.9	0.87	0.28	0.89	0.15	0.92	0.24	0.98	0.28	0.93	0.29	0.91	0.12	0.97	0.44

Fig. 5. Local rates of responding in Condition 5, in which stimulus duration was correlated with the inter-reinforcer interval, as a function of time since reinforcement and preceding stimulus duration.

and 11 as stimulus duration increased. The results were strikingly different from those of the previous conditions. Slopes of regression lines were invariably positive and the correlation coefficients were close to 1.0, in-

dicating a steady linear increase in response rate over time. Furthermore, the slopes of the regression lines declined steadily with stimulus duration, showing that the rate of increase was slower following longer stimuli.

DISCUSSION

In the crucial part of this experiment, rats were exposed to a procedure in which stimulus duration signaled the time separating stimulus offset and the availability of reinforcement. Consistent with previous findings from studies that investigated timing (Roberts & Church, 1978, Exp. 2) and a more general class of procedures used to investigate short-term memory in animals (e.g., Shimp, 1976), the rats in the present experiment responded differentially following different stimulus durations. However, the most interesting findings relate to the details of that differential responding.

Although there was no requirement to produce certain response patterns (unlike, for example, Shimp's [1982] procedure in which different temporally extended patterns were concurrently reinforced), the correlation between stimulus duration and the current interreinforcer interval strongly influenced responding. Although responding accelerated in all stimulus offset—reinforcer intervals, the rate of increase was linear and inversely related to the stimulus offset—reinforcer interval duration. This meant, for example, that rate might steadily increase from 0 to 2.0 responses/s in 10 s on one occasion and might increase (at a lower rate) from 0 to 2.0 responses/s in 20 s on another occasion. Thus, although the number of responses per interval increased with interval duration, average response rate did not change systematically with interval duration.

The procedure can be described as a series of FIs in which the duration of the current interval is signaled, and the accelerating pattern of responding might be thought similar to FI performance. This resemblance, however, is superficial. Although FI performance is usually described as "scalloped," scalloping is largely the product of a long and highly variable PRP (Shull, 1979) with an average value determined by the current FI value (Schneider, 1969; Shull, 1971). In contrast, in the present experiment poststimulus pauses (which are here equivalent to PRPs) were short and relatively constant

from interval to interval. Further, at FI values similar to the ones used here, rats typically show little or no acceleration within the local period of responding (Lowe & Harzem, 1977; McAuley & Leslie, 1983), but in the present experiment accelerating response patterns were consistently found. This seems to be a type of complex temporal control (Staddon, 1972) not previously described. This phenomenon warrants further investigation; it would be most interesting, for example, to know whether this temporal control could be produced with a nontemporal signaling stimulus, such as an auditory tone of varying frequency.

Both key features of the behavior, short variable pauses and accelerating response patterns, have been reported in previous studies of VI schedules. Consistent PRPs of several seconds were found in VI schedules, even when the minimum interreinforcer interval was near zero (Harzem, Lowe, & Priddle-Higson, 1978; Leslie, 1981) and arithmetic VI schedules generated accelerating response patterns (Catania & Reynolds, 1968; Leslie, 1981). Performance under the procedure used here might thus be described as appropriate to a series of arithmetic VIs in which the current mean interreinforcer interval is signaled.

The patterns of responding engendered when there was either no added stimulus or one with a fixed 6-s duration (Conditions 1 and 2) were consistent within and between animals, and resemble those found by Leslie (1981) on a VI schedule in which a very low rate of reinforcement was programmed for 10 s following reinforcement and a higher rate was programmed subsequently. He found that responding accelerated slowly for 10 to 15 s and then reached an asymptote, in similar fashion to that shown in Figure 1. When in the present experiment the duration of the added stimulus was varied (Conditions 3 and 4), responding was delayed until stimulus offset but the patterns were otherwise similar.

As the minimum interreinforcer interval always exceeded stimulus duration, these results might appear to support Staddon and

Frank's (1975) suggestion that the minimum interreinforcer interval is the main determinant of pause duration in interval schedules, but there is an anomaly. In Condition 4 the minimum interreinforcer interval was considerably longer than in Conditions 2 and 3 (see Table 1), but responding started at roughly the same time after stimulus offset. Furthermore, of the four rats moved from Condition 3 to Condition 5, three (R4, R6, and R9) showed no change in pausing and one (R7) showed a slight increase. Longer pausing was shown by one (R5) of the three rats moved from Condition 4 to Condition 5, but Staddon and Frank's conjecture cannot account for this because the minimum interreinforcer interval was the same in both these conditions. In fact only in Condition 1, in which no stimulus was presented and performance can be compared directly with that on various VI schedules studied by Leslie (1981), does minimum interreinforcer interval appear to be important. In the conditions in which a stimulus was presented, it is more parsimonious to say that responding began after a short, reliable poststimulus pause, whatever the duration of the preceding stimulus. This strong temporal control by stimulus offset persisted in Condition 4 and Condition 5, resulting in responding at times in the interreinforcer interval when reinforcement was never available.

The consistent short poststimulus pauses in the present study are similar to the PRPs on VI schedules reported by Harzem et al. (1978) and Leslie (1981). In those studies there was found to be an irreducible short PRP even when reinforcer presentation had minimal discriminative properties (cf. Staddon, 1972). Harzem et al. attributed this to an unconditioned suppressive effect of reinforcement. In the present study, the post-stimulus pause was independent of the reinforcement contingencies prevailing immediately after stimulus offset and may be due to an aftereffect of extinction-correlated stimuli—a possibility compatible with the suggestion of Harzem and his colleagues.

The present findings replicate those of earlier studies showing that the occurrence

of a stimulus within a VI schedule that is reliably related to the interreinforcer interval will influence responding (e.g., Stubbs, 1971; Van Haaren & Krafft, 1982). They extend those findings, however, by showing that signaling various interreinforcer intervals produces corresponding changes in behavior. More specifically, we examined two measures of performance and found that although poststimulus pause was not affected, the pattern of responding across the stimulus offset—reinforcer interval was controlled by a correlation between the duration of the stimulus and the interreinforcer interval.

Fixed-interval schedules have been used often as a vehicle for studying temporal control or timing (Richelle & Lejeune, 1980), but the responding generated shows persistent interval-to-interval variability (Zeiler, 1979) and other poorly understood dynamic fluctuations (Gentry & Marr, 1982). It is not even clear what the conditions are for accelerating or "break-and-run" (Schneider, 1969) response patterns within intervals. In contrast, the procedure developed here provides orderly temporal control where within-interval acceleration occurs and is related to the current interreinforcer-interval duration.

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