SCHEDULE-INDUCED DRINKING AS A FUNCTION OF INTERREINFORCEMENT INTERVAL IN THE RHESUS MONKEY[1]

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Lever presses by two rhesus monkeys produced food pellets that were assigned by both an ascending and descending series of fixed-interval schedules whose values varied between 1 and 512 sec. The amount of schedule-induced drinking was bitonically related to inter-reinforcement interval, reaching a maximum at approximately 120 sec and declining at longer fixed intervals. The relation between water intake and interreinforcement interval was complexly related to two drinking measures: (1) the probability of drinking following a pellet and (2) the amount drunk per bout. Drinking rate was also bitonically related to interreinforcement interval.

Key words: schedule-induced polydipsia, adjunctive behavior, fixed-interval schedule, reinforcement frequency, rhesus monkey

Falk (1961) originally demonstrated that rats, when food deprived and permitted to lever press for small pellets of food delivered at spaced intervals, drink excessive amounts of water in each postpellet period. This pattern of drinking has been labelled "schedule-induced polydipsia". One factor determining the magnitude of schedule-induced polydipsia is the length of time between pellet deliveries, the interreinforcement interval. Falk (1966) reported that as the interreinforcement interval of fixed-interval schedules increased from 2 to 180 sec, total water intake also increased. When the interreinforcement interval increased to 300 sec, total fluid consumption decreased sharply, yielding an inverse-U or bitonic drinking function over the total range. Subsequent investigators (Bond, 1973; Flory, 1971; Hawkins, Schrot, Githens, and Everett, 1972; Keehn and Colotla, 1971) using relative intake measures, such as milliliters consumed per pellet, have repeatedly confirmed the bitonic drinking function in rats, reporting peak water intakes at interreinforcement intervals between 120 and 240 sec.

Little systematic attention has been directed at the behavioral determinants that interact to produce the bitonic relation between water consumption and interreinforcement interval, and no studies have extended the generality of this relation to species other than the rat. Segal, Oden, and Deadwyler (1965) recorded the relations between a number of drinking measures and interreinforcement interval in rats exposed to response-independent food-reinforcement schedules. They reported the following effects as the interreinforcement interval increased from 30 to 480 sec: (1) the percentage of pellets followed by drinking was bitonically related to interreinforcement interval reaching peaks at intervals between 120 and 240 sec; (2) both the postpellet drink latency and drink duration increased monotonically throughout the interreinforcement interval range; and (3) the rate of licking during a drinking bout decreased monotonically throughout the interreinforcement interval range. However, they neglected to report session water-intake values to which these behaviors might be related. More recently, Keehn and Colotla (1971) reported water intake data that could be compared with the frequency of postpellet drinking but with no other quantitative measure. They demonstrated in rats that the amount of water ingested per pellet and the probability of drinking after a pellet were bitonically related to interreinforcement interval, and both reached peak values at an interreinforcement interval of 60 sec.

The present study presents systematic data on the relation between interreinforcement

interval and polydipsia in the rhesus monkey (*Macaca mulatta*). This species has previously been shown to engage in schedule-induced polydipsia (Porter and Kenshalo, 1974; Salzberg, Hinton, and Jordon, 1968; Schuster and Woods, 1966).

METHOD

Animals

Two adult, male rhesus monkeys, Jason and Tonto, served. Before this study their free-feeding weights were 14.6 and 11.4 kg, respectively. Both had previous experience with fixed-interval and second-order schedules of food reinforcement. For the duration of the study, the monkeys were housed in Lehigh Valley operant chambers (Model 1330C) which permitted 78 by 85 by 60 cm³ of unrestricted living space. The houselight was illuminated at 8 a.m. each day and remained on for a 12-hr light cycle, unless extended by the afternoon experimental session. Water was continuously available and 750-mg banana-flavored Noyes pellets, 140 of which were delivered daily as reinforcers, comprised the bulk of their diet. Supplements of Purina monkey chow and fruit were provided routinely to ensure a balanced diet and to maintain the monkeys at approximately 90% of their free-feeding weights throughout the study.

Apparatus

In each chamber, a primate response lever (LVE Model PRL-001/121-07) was centrally located on the front panel, 24 cm above the grid floor, and required approximately 25 g (0.25 N) to operate. A 7.5-cm by 7.5-cm square aperture located in the lower right-hand corner of the front panel provided access to the food magazine. A Hoeltge drinking tube was situated 29 cm directly above the magazine and protruded 1.5 cm into the chamber. Each contact between the grid floor and the tube activated a Skinner electric valve, which released a 1.0-ml aliquot of tap water at a regulated line pressure of 10 p.s.i. Gross observations made during sessions revealed that all tube contacts were made by the monkeys lips and that the aliquot of water was ingested. Solid-state programming and recording equipment were located in an adjacent room.

Procedure

The monkeys were presented the following ascending series of fixed-interval schedules, in which a pellet was delivered for the first lever press after a fixed interval of 1, 2, 4, 8, 16, 32, 64, 128, 192, 256, or 512 sec had elapsed since the previous reinforcer. The onset of white noise in the chamber signalled the start of each experimental session and, except for brief offsets, remained on during the session. A brief 2-sec offset of white noise accompanied the delivery of each food pellet, and the next interval was initiated with the re-instatement of the white noise. At the first 10 fixed-interval values, subjects received two sessions per day; the first started at 8 a.m. and the second at 4 p.m. Each session terminated after 70 pellets had been earned. At FI 512-sec, only one session, during which 70 pellets were delivered, was conducted daily. Each fixed-interval value was maintained until total session water intake showed no consistent change over eight consecutive sessions. Within sessions, licks were recorded during consecutive fourths of the interreinforcement interval and during the overflow period between reinforcer availability and delivery. Licks were also recorded for the periods between sessions, since the drinking circuit was continuously active.

When the ascending series of intervals was completed, a generally descending series of fixed intervals was presented to demonstrate the recoverability of intakes about the peak of the obtained drinking functions. Fixed-interval values of 192, 64, 32, and 128 sec were presented to Jason and values of 192, 128, and 64 sec were presented to Tonto.

RESULTS

Table 1 contains the sequence of schedules presented to each monkey, the number of sessions conducted at each FI value, and the various bar-pressing and drinking measures recorded during the study. The bar-pressing and drinking measures and the actual session duration (Columns 3 to 7) are mean values averaged over the last eight sessions of each FI value and constitute the data base from which the functions described in the remaining figures were computed.

Figure 1 divides daily water intake into that portion ingested during the two sessions and

Table 1

Order and number of sessions of Fl schedule presentations to each monkey together with means of the following dependent measures: bar presses per session, number of pellets followed by a drinking bout, total session water intake in ml, total between-session water intake in ml, and obtained session duration in seconds. Standard deviations are in parentheses. Data represent averages of the final eight sessions at each Fl schedule except Fl 128-sec during the decending series for Jason, which represents the average of all six sessions.

Subjects	Schedule Order (1)	Sessions (2)	Bar Presses (3)	Drinking Bouts (4)	Session Water Intake (ml) (5)	Between-Session Water-Intake (ml) (6)	Session Duration (sec) (7)
Jason				*Ascending Series*			
	Fl 1-sec	16	70.0	0.0	0.0	2128.2(226.0)	240
	Fl 2-sec	15	129.4	0.0	0.0	2259.0(267.9)	301
	Fl 4-sec	13	243.1	0.0	0.0	1448.0(251.4)	413
	Fl 8-sec	14	517.0	4.8(3.5)	102.9(64.1)	773.5(317.7)	742
	Fl 16-sec	18	770.2	20.4(3.5)	559.8(124.1)	407.8(201.1)	1,260
	Fl 32-sec	14	955.6	19.0(5.6)	900.8(173.8)	305.8(165.5)	2,345
	Fl 64-sec	12	877.5	21.4(3.9)	1173.2(129.6)	170.8(153.2)	5,026
	Fl 128-sec	29	2220.4	23.2(5.3)	1306.6(88.0)	464.0(368.1)	8,869
	Fl 192-sec	10	2321.6	16.8(3.1)	1089.1(152.6)	480.8(178.9)	14,245
	Fl 256-sec	40	1137.2	5.6(3.9)	272.4(156.2)	607.2(84.2)	25,739
	Fl 512-sec	25	2507.1	9.2(3.4)	518.6(214.3)	228.2(22.8)	59,934
				Descending Series			
	Fl 192-sec	12	1451.6	10.0(3.2)	1009.0(148.4)	624.5(78.0)	17,766
	Fl 64-sec	10	770.4	12.6(1.9)	1048.9(73.8)	511.8(193.2)	4,957
	Fl 32-sec	11	438.5	11.2(0.9)	807.0(104.3)	385.2(245.1)	2,730
	Fl 128-sec	6	1327.0	10.2(0.8)	1149.5(108.9)	613.3(281.0)	11,333
Tonto				*Ascending Series*			
	Fl 1-sec	13	70.0	0.0	0.0	526.2(138.4)	210
	Fl 2-sec	13	73.9	0.0	0.0	522.8(107.3)	280
	Fl 4-sec	14	70.0	0.0	0.0	495.2(150.8)	434
	Fl 8-sec	10	71.9	2.8(1.3)	54.5(22.6)	471.0(86.1)	910
	Fl 16-sec	10	107.5	5.5(1.3)	150.0(39.4)	328.2(46.2)	1,505
	Fl 32-sec	12	127.5	20.1(6.1)	296.5(97.7)	143.0(73.5)	2,555
	Fl 64-sec	12	176.6	39.6(9.0)	662.1(79.9)	409.8(151.7)	5,145
	Fl 128-sec	17	501.2	36.0(4.9)	940.0(102.6)	362.8(138.6)	10,262
	Fl 192-sec	22	549.9	18.0(4.0)	811.5(199.6)	451.0(189.7)	15,400
	Fl 256-sec	34	811.6	17.4(3.2)	752.8(84.9)	396.5(143.3)	20,790
	Fl 512-sec	21	736.9	8.8(1.3)	606.2(123.2)	671.0(109.3)	41,069
				Descending Series			
	Fl 192-sec	14	864.5	10.5(2.5)	564.9(50.8)	489.8(101.3)	14,098
	Fl 128-sec	10	689.5	9.9(1.9)	600.9(187.2)	270.8(128.2)	9,478
	Fl 64-sec	10	337.0	41.5(1.9)	452.2(84.1)	610.8(58.9)	4,760

that ingested outside the sessions and portrays their interaction as the reinforcement schedule varied. Thus, the daily session intake shown in Figure 1 is twice the values listed in Table 1 (Column 5) for all schedules except FI 512-sec, when only one session was conducted daily. Within- and between-session water intake is plotted as a function of the obtained interreinforcement interval at each FI schedule, computed by dividing session duration (Column 7) by 70, the number of pellets delivered. Since within-session drinking did not occur during the first three fixed-interval values for either monkey, the daily between-session intakes at these values reflect the daily homeostatic water requirement associated with a daily diet of 140 pellets. Jason's daily water intake was substantially greater than that of Tonto. As schedule-induced drinking developed and session intake increased with longer interrein-
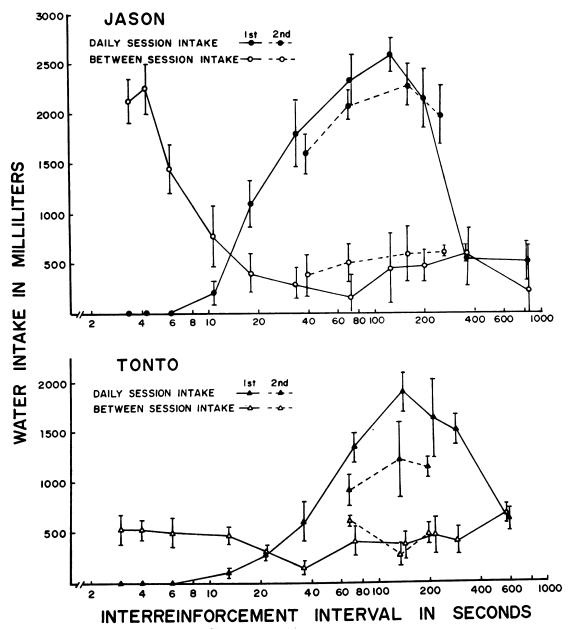
Fig. 1. Daily within-session and between-session water intake in milliliters as a function of interreinforcement interval during both the ascending (solid lines) and descending (dashed lines) series. Session intake values represent daily totals of both morning and afternoon sessions and were derived by doubling the mean session. intakes in Table 1 (Column 5) for FI 8-sec through FI 256-sec schedules, where two sessions were conducted daily. Thus, when session intake is added to the between-session complement at each schedule value, total daily water intake results. Standard deviation markers are erected vertically through each data point, and the x-axis is logarithmic for compact presentation.

forcement intervals, there was a corresponding drop in water intake outside the session for both monkeys; the inverse relation between these two functions was more marked with Jason than with Tonto. Schedule-induced

drinking emerged at interreinforcement intervals of 10.5 sec and 13 sec respectively for Jason and Tonto, increased to peak intakes at 128 sec for Jason and 150 sec for Tonto, and then declined again at longer intervals, de-

scribing a bitonic function for the ascending series of intervals. During the descending series, both the form of the session-intake functions and the location of the peaks were similar; however, the amount of water ingested during the session was reduced overall for both monkeys.

There are various criteria for determining the degree of polydipsia (Falk, 1969). For the present study, water intake during the nearly 8-hr period between the morning and afternoon sessions at the FI 1-sec schedule was selected as a baseline measure of extra-schedule drinking induced by food ingestion alone, since it was comparable in length to session durations produced by the longer FI schedules but was not preceded by within-session drinking. Jason's baseline intake was 935.0 ml (SD = 118.6) and Tonto's was 203.2 (SD = 86.6). Schedule-induced polydipsia, which was then defined as a ratio of session intake (Column 5) to baseline intake that exceeds 1.0, did not reliably occur until exposure to FI 32-sec for Tonto and FI 64-sec for Jason. Polydipsia persisted throughout the remaining schedules for Tonto and until FI 256-sec for Jason.

Panel A of Figure 2 describes the relation between water intake and interreinforcement interval in the form in which it has commonly been reported. The milliliters of water ingested per pellet, obtained by dividing session intake (column 5) by the number of pellets delivered per session (70) is plotted as a function of the obtained interreinforcement interval at each FI schedule. These bitonic functions were representative of both morning and afternoon performance. While both monkeys generally drank more water per pellet in the afternoon session, the average difference was small, 1.0 ml for Jason and 0.5 ml for Tonto, and separate functions relating morning and afternoon intakes with interreinforcement interval were very similar.

In Panel B of Figure 2, the per cent of intervals per session in which a drinking bout occurred is plotted as a function of the obtained interreinforcement interval. The per cent of intervals measure was computed by dividing the number of intervals containing at least one lick (Column 4) by the total number of intervals in the session, *i.e.,* 70. The per cent of intervals containing drinking increased systematically to peak values of 33 at the 128-sec interreinforcement interval for Jason and 57

at the 150-sec interreinforcement interval for Tonto, then declined sharply at longer interreinforcement intervals during the ascending series only. Throughout the descending series, the per cent of intervals containing drinking remained near 15, apparently locked at the percentages obtained at the last FI schedule in the ascending series. The ascending-series function was decidedly bitonic and resembled the ml-per-pellet function presented in Panel A, except that the slope of the descending limb was considerably steeper.

In Panel C of Figure 2, the ml ingested per bout, computed by dividing the session intake values in Column 5 of Table 1 by the number of bouts in Column 4, is plotted as a function of the obtained interreinforcement interval. During the ascending series of intervals, the amount ingested per bout increased throughout the range of interreinforcement intervals for both monkeys. The function was also obtained during the descending series; however, the amount ingested per bout was higher overall for both monkeys.

The drinking patterns that developed during each FI schedule in the ascending series are displayed in the cumulative records in Figure 3. Licks advanced the response pen, which reset to baseline and recorded a diagonal mark with each pellet delivery. Gross observation revealed that when a drinking bout occurred within the session, it was during the postpellet period. For Jason, the latency between pellet delivery and drinking onset clearly increased with increasing interreinforcement interval; for Tonto, drinking latency was short (12 to 20 sec) and did not vary appreciably as interval size varied. With Jason, local licking rate appeared to remain constant throughout the series but pauses developed within drinking bouts, 'particularly at FI values of 256 and 512 sec. However, with Tonto, the local licking rate appeared to decline as interreinforcement interval increased.

The drinking and bar-pressing distributions in Figure 4, provide a quantitative description of how the two behaviors were distributed during consecutive fourths of the fixed interval as interval size varied. For Jason, drinking was distributed throughout the interreinforcement interval regardless of its length. With the exception of the drinking pattern at FI 8-sec, which peaked in the overflow period, Jason's
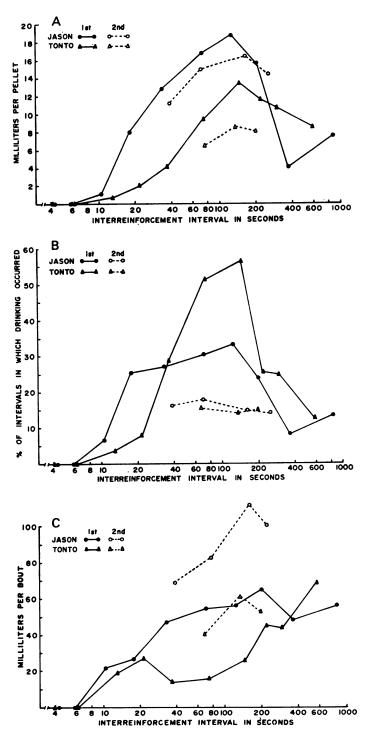
Fig. 2. Panel A. Milliliters per pellet ingested as a function of interreinforcement interval in seconds during both the ascending (filled symbols) and descending series (open symbols). The x-axis is logarithmic for compact presentation. Panel B. Per cent of intervals per session in which a drinking bout occurred as a function of interreinforcement interval in seconds during both the ascending (filled symbols) and descending series (open symbols). Panel C. Milliliters of water ingested per drinking bout as a function of interreinforcement interval during both the ascending (filled symbols) and descending series (open symbols).
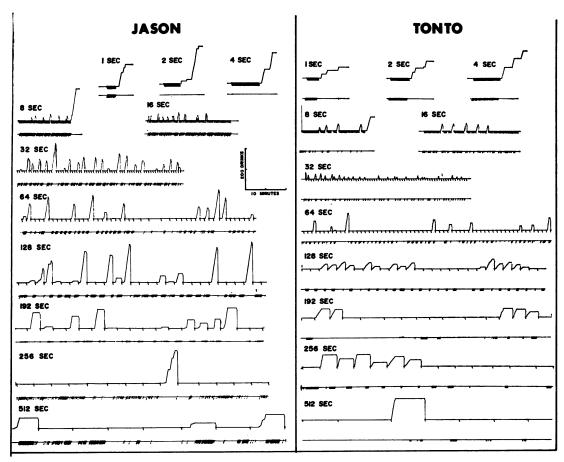
Fig. 3. Cumulative records of an entire session at interreinforcement intervals from 1 to 64 sec and of a representative portion of a session at interreinforcement intervals from 128 to 512 sec during the ascending series only. Licks on the drinking tube advanced the response pen, which reset and recorded an oblique hatchmark at the completion of each interval. All lever presses, except those that completed an interval, were recorded by the event marker at the bottom of each record.

drinking peaked during the second fourth of the interval and fell systematically over the remaining periods of the interval at each interreinforcement interval. Jason's bar-pressing rate was fairly constant throughout the smaller intervals, but became more positively accelerated as the interval size increased. Tonto's drinking distributions were much steeper and displayed a sliding mode that originated in the overflow period at FI 8-sec and shifted to earlier portions of the interval as the FI value increased. Tonto's bar-pressing rates were positively accelerated at all fixed intervals that supported schedule-induced drinking.

Recently, the relation between drinking rate and interreinforcement interval has been emphasized because of the functional similar-

ity it may bear with the relationship between the rate of operant behavior and reinforcement frequency (Hawkins *et al.*, 1972). In Figure 5, both ingestion rate and bar-pressing rate, computed by dividing session water intake (Column 5) and bar presses (Column 3) by session duration (Column 7) are plotted as a function of obtained interreinforcement interval. The ingestion rate functions produced by the monkeys were clearly bitonic. Ingestion rate reached a maximum at interreinforcement intervals of 18 sec for Jason and 73.5 sec for Tonto. The descending limbs produced by the ascending series of intervals were similar for the descending series. The bar-pressing functions differed between monkeys but neither closely resembled the ingestion-rate functions. Tonto's bar-press rate was nega-
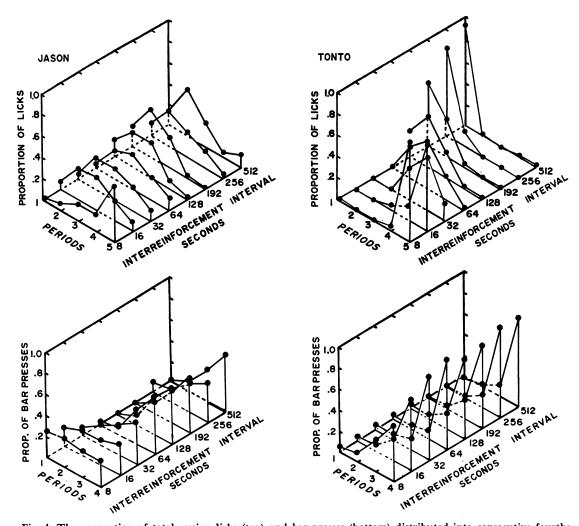
Fig. 4. The proportion of total session licks (top) and bar presses (bottom) distributed into consecutive fourths of the interval plus an overflow period. A family of curves relating these functions to ascending interreinforcement values is arrayed from front to back. Drinking and bar-pressing distributions are included from the ascending series of interreinforcement intervals only.

tively decelerated throughout the fixed-interval range, while Jason's was bitonic but peaked at a shorter interval than did the ingestion rate.

DISCUSSION

In most respects, the water-intake functions depicted in Figure 1 and Figure 2 (Panel A) bear a remarkable resemblance to those produced by rats. The absolute quantity of water ingested per pellet by the monkeys was about 15 times that normally ingested by the rat; however, if water intakes are expressed in terms of amount of food consumed during the session, the ratios for monkeys and rats are very similar. For instance, at the FI 128-sec schedule, which produced maximal drinking, Jason ingested 1306.6 ml of water and 52.5 g of food (0.75 g × 70 pellets), yielding a water to food intake ratio of 24.9 ml/g; Tonto ingested 17.9 ml/g. Based on data provided by Flory (1971), rats presented with a similar interreinforcement interval ingested an average of 18.9 ml/g (range = 20.6 to 16.5 ml/g).

The bitonic drinking functions were in turn related to the following two component behaviors: (1) the probability of initiating a drinking bout following a pellet and (2) the quantity of water consumed during such a bout. The probability of drinking (see Panel
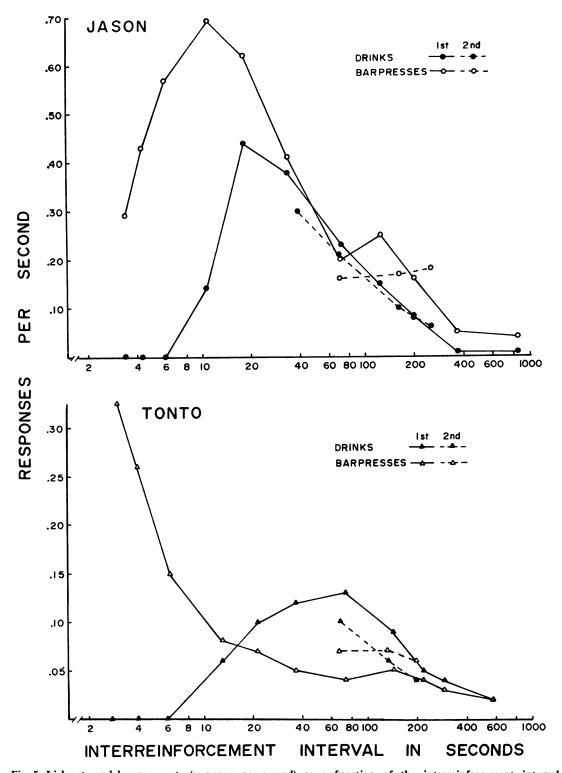
Fig. 5. Lick rate and bar-press rate (responses per second) as a function of the interreinforcement interval during both the ascending (solid lines) and descending series (dashed lines). The x-axis is logarithmic for compact presentation.

B, Figure 2) was a nearly symmetrical bitonic function of the interreinforcement interval during the ascending series, and produced the bitonicity of the ml-per-pellet function and the location of its peak. When compared with similar functions produced by rats, it could be remarked that the probability of initiating a drink following a pellet was substantially less than the peak 85 to 95% values reported by Segal *et al.* (1965) and by Keehn and Colotla (1971) for rats. By comparison, neither monkey reached 60%. This may either represent a species difference or more probably a motivational difference. The rats used by Segal *et al.* (1965) were held at 80% of free-feeding weights while those of Keehn and Colotla (1971) were maintained at 85% of a free-feed weight determined more than six months before the experiment; the monkeys were maintained at or above 90% free-feeding weight. Falk (1969) clearly demonstrated that polydipsia decreased in rats as they reached free-feeding weight, and it is reasonable to presume that a decrease in the probability of drinking accounted for part of the loss. The magnitude of the drinking bout (see Panel C, Figure 1) increased monotonically as a function of interreinforcement interval and thus accounted for the asymmetry in the ml-per-pellet gradient, that is, the flatter slope of its decreasing segment. It is interesting to note that similar water-intake functions were produced by both monkeys despite marked differences in their intra-interval drinking patterns. It does not seem likely that differences in bar pressing between monkeys accounted for differences in their drinking patterns because, as Figure 3 indicates, pressing and drinking behaviors prevailed at different periods of the interval for all fixed-interval values but the shortest. Jason's bar-pressing rate was generally higher during the earlier portions of the interval than Tonto's; however, had bar pressing directly interfered with drinking, Jason's drinking bout should have been displaced to an earlier period of the interval than Tonto's, which was not the case.

During the descending series of fixed intervals, the ml-per-pellet functions were closely replicated in form; however, their component functions were not. In fact, the controlling roles of the component functions appeared to be reversed. The probability of drinking following a pellet remained low and constant with decreasing interval size, while the magnitude of the drinking bout increased dramatically and the function exhibited bitonicity. The interaction of these reversed relationships resulted in recapturing the shape of the original function. We are unable, at present, to account for this reversal between series, but the fact that it occurred in both animals suggests that an important sequence effect was operating. Nevertheless, it would appear that bitonicity in the composite drinking curve is a robust phenomenon, which is not dependent in any simple or immutable way on changes in either the probability or magnitude of the drinking bout with changes in interreinforcement interval.

The finding that the quantity of water consumed per bout increased systematically with increases in the interval between pellet delivery may help to resolve an apparent paradoxical finding of a similar relationship recently obtained with rats whose lever presses were reinforced on a percentage reinforcement of fixed intervals (Allen, Porter, and Arazie, 1975). As the per cent of 60-sec intervals terminating with a pellet was decreased, drinking following pellets increased even when the mean interreinforcement interval was far in excess of 120 to 180 sec. The authors offered a contrast interpretation of this phenomenon, which would appear to be equally applicable here. Indeed, positive contrast effects have recently been demonstrated in rats with schedule-induced drinking when a standard behavioral contrast design was used (Allen and Porter, 1975).

Hawkins *et al.* (1972) noted that polydipsic drinking, an adjunctive behavior, and operant behavior bear marked similarities when the rates of both behavior classes are related to interreinforcement interval. They further speculated that the strength of these two behavior classes are therefore determined by the same underlying reinforcement processes. For instance, Catania and Reynolds (1968) demonstrated that the relation between rate of key pecking in pigeons and interreinforcement interval was a positively accelerated decreasing function between intervals of 12 to 360 sec. Plotting ingestion rate in a similar manner, but between interreinforcement intervals of 60 and 360 sec, also permitted Hawkins *et al.* (1972) to report monotonically decreasing functions. However, the ingestion-rate func-

tions depicted in Figure 5 indicate that their conclusions suffered from overgeneralization. While both ingestion-rate functions are monotonically decreasing at interreinforcement intervals greater than 60 sec, thus replicating those provided by Hawkins *et al.* (1972), both functions clearly turn around at interreinforcement intervals between 12 and 60 sec, a range where bar-press rates are falling monotonically for both monkeys. As shown by Jason's data, bar-press rates may turn around at intervals below 12 sec, the lowest value used by Catania and Reynolds (1968), thus limiting the generality of their findings also. The difference between the ingestion-rate and bar press-rate functions of the present study casts doubt on any proposal attempting to unify the action of a reinforcer on these two behavior classes. It would be theoretically appealing and parsimonious to state that manipulation of the parameters of the reinforcer resulted in universally commensurate changes in its reinforcing and inducing properties, and there exists some evidence that functional similarities do occur. For example, changes in deprivation (Falk, 1969) and pellet magnitude (Flory, 1971; Hawkins *et al.*, 1972) would appear to affect the reinforcing and inducing operations of the reinforcer in basically similar ways, in that increases in both variables usually lead to increases in either behavior. Furthermore, behavioral contrast effects may be demonstrated with both reinforced and induced behaviors (Allen and Porter, 1975; Jacquet, 1972). However, it is becoming apparent that the two behavior classes react in different ways to systematic changes in the palatability of the pellet (Christian, *in press*) and, as herein shown, to reinforcement density as well. A clearer profile of the interrelations between the reinforcing and inducing operations of a reinforcer awaits further systematic study.

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