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EATING AND DRINKING: AN ECONOMIC ANALYSIS

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Food-deprived rats were exposed to various schedules of food delivery; water-deprived rats were exposed to various schedules of water delivery. Eating and drinking were measured over sessions and at points throughout sessions. The symmetries and asymmetries of food and water consumption were explored in terms of: (1) substitutability of food versus water, and of food and water on the one hand versus leisure on the other, (2) constraints imposed by various schedules of food and water, and (3) the tendency of rats to maximize utility within the imposed constraints.

Key words: maximizing, matching, polydipsia, polyphagia, schedule-induced behavior, substitutability, choice, eating, drinking, rats

Eating and drinking have, heretofore, been studied as separate behavioral phenomena or, when studied together, have been treated asymmetrically. In operant conditioning research, eating has typically been used as a reinforcer (with food-deprived animals), whereas drinking, when it has been studied, has been studied as adjunctive behavior (Staddon, 1977).

This asymmetry of treatment seems to reflect an asymmetry of behavior; when food is restricted by a schedule of reinforcement, food-deprived animals drink excessively (Falk, 1961); the symmetric phenomenon, excessive eating by water-deprived animals exposed to schedules of water delivery, has rarely been observed (Roper, 1981). In other words, schedule-induced polydipsia is common, but schedule-induced polyphagia is rare. It is not entirely clear, however, whether schedule-induced polyphagia is rare because it is uncharacteristic of behavior or because it has so seldom been looked for. The purpose of the present experiments, therefore, is to study eating and drinking by rats with symmetric parameters of deprivation and availability varied over a wide range so as to observe symmetries and asymmetries of eating and drinking in a more balanced way than has been typical.

Previous accounts of eating and drinking (summarized by Staddon, 1977) have tended to separate instrumental reinforcers and adjunctive activities, with the latter given a secondary role. The very designation, "adjunctive," emphasizes the secondary nature of such behavior.

Adjunctive behavior is frequently compared to the displacement activities studied by ethologists. Most current accounts also view adjunctive behavior as a biological disturbance or anomaly on a more purely instrumental substrate. In Staddon and Simmelhag's (1971) terms, adjunctive behavior is accounted for by the principles of behavioral variation as opposed to the principles of reinforcement. The purpose of the economic analysis presented here is to try to bring adjunctive and instrumental behavior into a single theoretical framework.

An animal is viewed by economic theory as choosing a "package" of activities from among all available packages. The set of packages available is determined by constraints imposed by the time of availability of the commodities and the schedule of reinforcement. The organism's preference among available packages is determined by the mutual substitutabilities of the activities that comprise the package. From this viewpoint, consumption by a hungry animal of periodically delivered food is no more fundamental than that animal's consumption of freely available water. Consumption of the two commodities is seen, rather, as part of a balanced choice among a set of activities more

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or less substitutable for each other. That set comprises not only eating and drinking but also the instrumental response and other activities available in the experimental situation. An economic model has been applied by Rachlin (1978) and Rachlin, Battalio, Kagel, and Green (1981) to instrumental behavior with single and concurrent schedules of reinforcement. The present account extends the application of the theory to adjunctive behavior.

The schedule-induction paradigm emphasizes rate of response and asymmetry of food and water consumption. The first experiment reported here was essentially a replication of this paradigm, first with schedules of food and then with schedules of water delivery. However, in the second experiment, in order to make the results more amenable to an economic analysis (in terms of substitutability), the procedure differed from that ordinarily used. First, to make eating and drinking (and other activities) commensurable, rate of response and rate of reinforcement were translated into time spent consuming food and water. Second, to provide data for a molecular analysis, a single schedule of food or water delivery was programmed for an extended period of consumption measured continuously throughout the session.

EXPERIMENT 1

METHOD

Subjects

Four experimentally naive male albino rats about three months old at the start of the experiment (Numbers 2, 3, 4, and 5) served. Their average free-feeding weight was 550 g.

Apparatus

The experimental chamber was a standard operant chamber 30 cm wide, 24 cm long, and 20 cm high. The front panel contained a retractable lever mounted so its center was 7.6 cm from the floor and 2.5 cm from the left wall. A downward press of at least .1 N operated the lever. A hopper, supplied by a pellet feeder, was centered on the front panel 1.6 cm above the floor. A retractable drinking tube was mounted 2.5 cm from the floor and 4.5 cm from the right wall. The chamber was illuminated by two 6-W clear lights mounted on the front panel. Masking noise was provided by an exhaust fan. Standard electromechanical equipment in another room counted lever presses, operated the pellet feeder, and retracted the lever and the drinking tube. A drinkometer circuit counted licks.

Deprivation Conditions

Two conditions of deprivation were imposed: food deprivation and water deprivation. During food deprivation rats had free access to water in their home cages and sessions were run with rats at 80% of their free-feeding weights. If a rat weighed less than this amount at the end of a session, it was fed the difference between its weight and the 80% weight. If a rat weighed more than this amount before a session was scheduled to begin, the session was canceled for that day and the rat was not fed. During water deprivation rats had free access to food in their home cages and were deprived of water for 23 hours before each experimental session. For 15 min after each (45 min) session, they were allowed to drink freely in their home cage.

Procedure

There were two phases of this experiment—food restriction and water restriction. During the food-restriction phase, rats were deprived of food in their home cages and access to food was restricted during the experimental session. During the water-restriction phase, rats were deprived of water in their home cages and access to water was restricted during the experimental session. All rats were first exposed to the food-restriction phase and then to the water-restriction phase. Rat 5 died during the water-restriction phase so only the data of the remaining three rats will be presented for that phase.

Food and water reinforcers could be made available for brief periods. When a food reinforcer was scheduled, the lever was presented. Then a single press of the lever caused three 45-mg (Noyes) pellets to be delivered at half-second intervals. If the lever was not pressed, it was retracted after 8 sec. A water reinforcer consisted of presentation of the drinking tube. The tube was retracted after either 25 licks or 8 sec, whichever came first.

Because the lever or drinking tube was presented at variable temporal intervals, independent of the rat's behavior, the schedules of reinforcement used in these experiments may be considered variable-time (VT) schedules and will be identified as such hereafter. Technically, an 8-sec limited hold, signaled by the insertion of the lever or the tube, was appended to the VT schedule. In addition to the VT schedules, continuous reinforcement (crf) schedules (continuous availability of the lever or tube) and extinction (ext) schedules (unavailability of the lever or tube) were programmed as described below.

During the food-restriction phase, water was continuously available in home cages and the drinking tube was continuously available during experimental sessions. The rats were exposed to a series of schedules of food delivery ranging between continuous availability (crf) in which food and water were both freely available and extinction (ext) in which no food was available. The series was: crf; VT 20-sec; VT 30-sec; VT 1-min; VT 2-min; VT 4-min; VT 8-min; ext. Two rats (4 and 5) started at crf and were exposed to each schedule in order. (Here and throughout this experiment each exposure to a schedule lasted for 15 daily sessions.) Then the rats were exposed to the schedules in reverse order ending at crf again. This constituted a cycle. Both rats were run through two cycles. The other two rats (2 and 3) started at ext and were also run through two cycles. The VT-schedule intervals were distributed as suggested by Fleshler and Hoffman (1962). The duration of each session was 45 min. The session timer ran continuously throughout the session (it did not stop during reinforcement). The VT-schedule timer stopped when the bar was presented and started again after the third pellet was delivered. Thus the maximum number of reinforcers was somewhat less than would be obtained by dividing the session time by the normal interreinforcement time. The food-restriction phase was similar, essentially, to experiments studying schedule-induced polydipsia (e.g., Falk, 1961; Flory, 1971). Water was continuously available and food was delivered at varying intervals.

The water-restriction phase was symmetrical to the food-restriction phase. Food was available in home cages and the lever was continuously present (crf) during experimental sessions. Water reinforcers were made available according to the same series of schedules as food reinforcers in the previous phase. Rats 2 and 3 were started at crf and run through two cycles. Rat 4 was started at ext and run through two cycles. During the first cycle, regular Purina rat chow was freely available in the home cages. During the second cycle, Noyes pellets (the same kind used as reinforcers in the experimental session) were freely available in home cages. Again, the sessions lasted a total of 45 min and the VT timer stopped while the drinking tube was present.

RESULTS

Rates of response and reinforcement were calculated as number of responses or reinforcers divided by 45 min (the session time). There were no systematic differences between the first and second cycles or, except for a small degree of hysteresis, between upward and downward legs of a given cycle in either phase of this experiment. Each data point shown is an average of 10 sessions—the last five sessions of a condition on the upward leg and the last five sessions of that condition of the downward leg of the second cycle.

Food Restriction

Figure 1 shows the results of the food-restriction phase. The circled points represent the consumption of the four food-deprived rats during the 45-min sessions with both food and water freely available (crf). Rat 4 developed a pattern of licking that distorted the measure of rate of licking. That rat did not lick but kept its tongue on the drinking tube, vibrating it at a high rate. This caused an irregular flow of water into its mouth and abnormally high readings on the lick counter. The rat did not consume more water than the other rats, but it did spend more time at the drinking tube; this extra time might have interfered with its eating because the latency with which it pressed the food-delivery bar was considerably greater than that of the other rats at all but the lowest food delivery rates.

The points connected by solid lines represent average consumption by a rat during an entire session with access to food restricted by the various VT schedules. The crosses on the vertical line labeled 0-0 on the left of the ordinate represent lick rate of each rat during the extinction condition.

All four rats drank more when food was available on certain VT schedules than when food was freely available (crf) or unavailable (ext). This is schedule-induced polydipsia. The

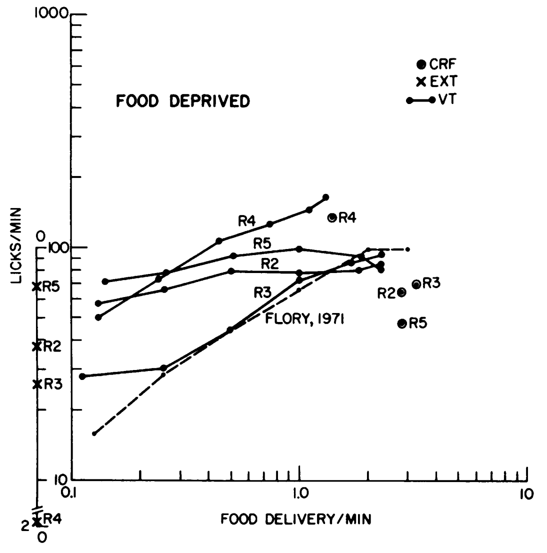

Fig. 1. Rate of licking at a water spout during a 45-min session as a function of rate of food reinforcement for four food-deprived rats. The crosses on the vertical axis 0-0 to the left of the ordinate represent rate of licking during extinction. The circled points represent rate of eating and licking during free accessibility of food and water (crf). The dotted line represents data obtained by Flory (1971).

dashed line in Figure 1 shows data from Flory's (1971) study with rats using fixed-interval schedules and two pellets per reinforcement as plotted by Staddon (1977). (The session time varied in Flory's study, so those data are not strictly comparable with those obtained with fixed 45-min sessions in the present study.) Flory found that the drinking with two-pellet reinforcers was greater than that with one-pellet reinforcers. The somewhat higher rates of drinking with three-pellet reinforcers in the present study are therefore not inconsistent with previous results. Note, in Figure 1, that only Rat 5 shows a bitonic response function. The functions for the other rats increase continuously as the food schedule becomes more frequent. The functions for all the rats would have been bitonic if they were connected to the crf points.

With all schedules studied, rats occasionally failed to press the lever within the 8 sec of its availability. But once they pressed the lever, they ate the food delivered. The rats never left more than one or two pellets uneaten in the hopper during a session.

Water Restriction

Figure 2 shows the results of the water-restriction phase. (Rat 5 died during this phase, and Rat 4 did not exhibit the peculiar form of licking that it had in the food-restriction phase. The data for this rat are therefore closer to those of the other two rats than they were previously.) The circled points represent consumption by the three water-deprived rats at the end of the session with both food and water freely available (crf). The crf points are at a rate of about four water deliveries per min. This corresponds to a licking rate of 100 licks per min. Thus, Rats 2 and 3 drank more water in the crf condition of this phase (when water deprived) than they did at the highest rate of polydipsic drinking of the previous phase (when food deprived). As in the first phase, rats occasionally refused offered reinforcers—in this phase by failing to lick the tube during its 8-sec presentation.

None of the three rats ate more when water was restricted than they did when water was freely available. There was, therefore, apparently no schedule-induced polyphagia symmetrical to schedule-induced polydipsia (but we will return to this point later).

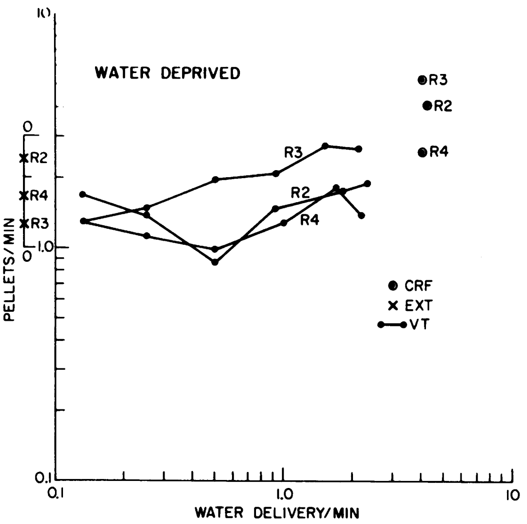

Fig. 2. Rate of eating during a 45-min session as a function of rate of water reinforcement of three water-deprived rats. The crosses on the vertical axis 0-0 to the left of the ordinate represent rate of eating during extinction. The circled points represent rate of drinking and eating during free accessibility of food and water (crf).

DISCUSSION

The results for the two phases of the experiment are symmetrical in certain respects and asymmetrical in others. Let us first discuss the symmetries. Consider the extinction conditions. Obviously, food-deprived rats consume some water, and water-deprived rats consume some food, when the other commodity is completely unavailable.

Next consider the other extreme, the crf points (circled). Except for Rat 5, food-deprived rats drank more when food was freely available (crf) than they did when food was completely absent (ext). Water-deprived rats ate more when water was freely available (crf) than when water was completely absent.

Another symmetry of the two phases of the experiment is that in both phases rats occasionally refused reinforcers (failed to press the lever or lick the tube during an 8-sec presentation) even when the rate of delivery was much less than that consumed freely. The reason for this may be that rats tend to consume a freely available commodity, of which they have been deprived, mostly at the beginning of a session. If the commodity is doled out periodically and rats are prevented from "tanking-up," they may not make up later for what they have missed initially (the second experiment examined this possibility more systematically).

Finally, the response functions (the points connected by solid lines) tend to rise in both phases of the experiment. That is, adjunctive eating and drinking both tend to increase with increasing rate of delivery of the deprived commodity.

The most significant asymmetry evident in Figures 1 and 2 is the position of the crf (circled) points relative to the food and water response functions (solid lines). If one follows the direction in which the response functions point, the circles are above the extended water-response functions, whereas the circles are below the extended food-response functions. If we consider the crf circles to be "normal" consumption, then the food-restricted (and deprived) rats drank too much and the water-restricted (and deprived) rats ate too little by the end of the session.

One way in which interval schedules of reinforcement may constrain behavior is that they force a more uniform consumption pattern on what would normally be a negatively accelerated consumption pattern. The observation of anomalies such as schedule-induced polydipsia may depend on this aspect of the constraint. But the measured effects of a pattern of consumption that varies over a session would, in turn, depend on the point within the session at which observations were made (or, alternatively, on the session duration). Meaningful analysis of the effects of schedule constraints on eating and drinking thus can only be done on a more molecular level than the data of Experiment 1 allow. Specifically, such analysis would require moment-by-moment measurement of consumption during crf and VT-schedule sessions. The purpose of Experiment 2 was to provide such measurement.

EXPERIMENT 2

METHOD

Subjects

Four experimentally naive male albino rats about 3 months old at the start of the experiment (Numbers 36, 37, 38, and 39) served. Their average free-feeding weight was 536 g.

Apparatus

The apparatus was the same as in Experiment 1.

Procedure

Two rats (36 and 37) were food deprived and two rats (38 and 39) were water deprived as in Experiment 1. Sessions in this experiment were always 3 hours in duration. Because rats became satiated during the long sessions, days were frequently skipped when rats were overweight. Each rat was run first for 10 sessions with both commodities freely available (crf), then for 10 sessions with the deprived commodity available on a VT 20-sec schedule, then for one session with both commodities freely available but only until a certain amount, *k*, of the deprived commodity had been consumed. Then that commodity was withdrawn. The calculation of *k* was different for each rat and will be explained later. This last condition is like the massed-reinforcer baseline suggested by Roper (1981).

After these three conditions were run, Rats 36 and 37 were water deprived, Rats 38 and

39 were food deprived, and the three conditions were repeated in the same order.

Results

In order to compare eating with drinking, the two consummatory responses were converted into times (Baum, 1976). Time drinking was calculated for all rats as six licks per sec on the basis of informal observations. If, for instance, a rat licked the water spout 600 times during the first 5 min, it was assumed to be drinking for 100 sec of the first 5 min. Time eating was calculated separately for each rat by assuming that food-deprived rats with food and water freely available (crf) spent the first 5 min of the session eating and drinking and doing nothing else. Time drinking during this first 5-min period was subtracted from 5 min and the difference divided by the number of pellets eaten. Determined in this way, the time per pellet for Rats 36, 37, 38, and 39 was 4.2 sec, 3.4 sec, 4.9 sec, and 5.2 sec. The data shown are averages of all sessions at each condition.

Food Deprivation

Figure 3 shows cumulative time spent eating and drinking in the free-food phase with food freely available (corresponding to crf in Experiment 1). Vertical lines mark the end of the first and second hours of the session. During the first 5 min, the hungry rats ate (as opposed to drinking) almost exclusively. Then eating gradually slowed over the first hour. The almost horizontal cumulative curves indicate virtually no eating during the second hour. Finally, during the third hour, eating increased again slightly. Except for the first 5-min period when drinking was practically nil, the drinking curves follow the eating curves but on a lower level.

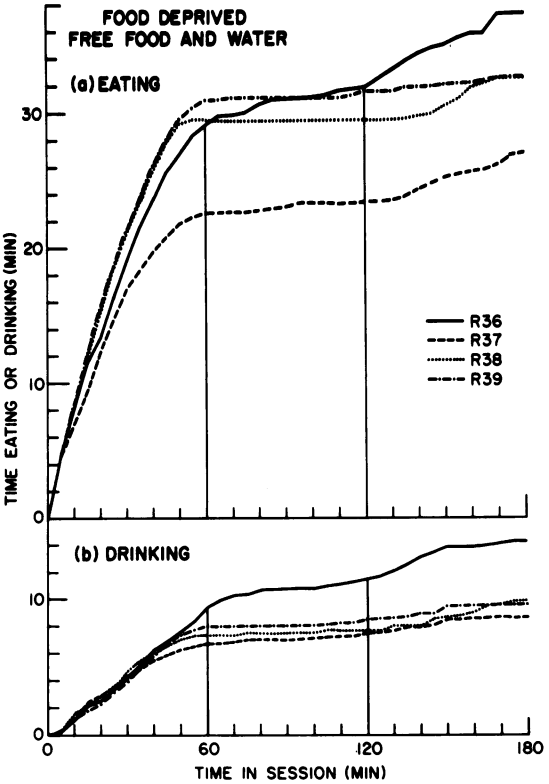

Fig. 3. Cumulative time spent (a) eating and (b) drinking by four food-deprived rats during a 3-hour session with free access to food and water (crf).

Figure 4 shows corresponding data for the VT 20-sec phase. With VT 20-sec, eating was steady at first but slower than with free food (because the VT schedule prevents rapid eating). The rats ate for a longer time before leveling off and the subsequent reacceleration of eating was also retarded (for Rat 38, never appearing). Drinking was only barely suppressed during the first 5 min (no competition from the now-constrained eating) and again followed the pattern of eating but at a higher level than with free food (schedule-induced polydipsia). The relative levels of free-food eating versus VT-food eating and drinking are shown in Figure 5 where averages of the four rats are plotted for each condition. The order of the four conditions and the pattern of consumption within each condition were the same for all rats. The suppression of eating caused by the VT schedule seems to be compensated by the elevation of drinking. This is shown more clearly in Figure 6 in which the sum of eating and drinking times (consumption) in the free-food condition is compared with the sum of eating and drinking time in the VT-food condition for each rat. All functions show the same pattern. Consumption started out at a rapid rate under both conditions and was slightly greater for free food than VT food. But the high consumption rate persisted longer with VT food so that the curves cross near the end of the first hour of the session (at an average of 64 min). After crossing, consumption of food and water halted abruptly with VT food but continued upward slightly with free food. By the end of the session, the rats had spent

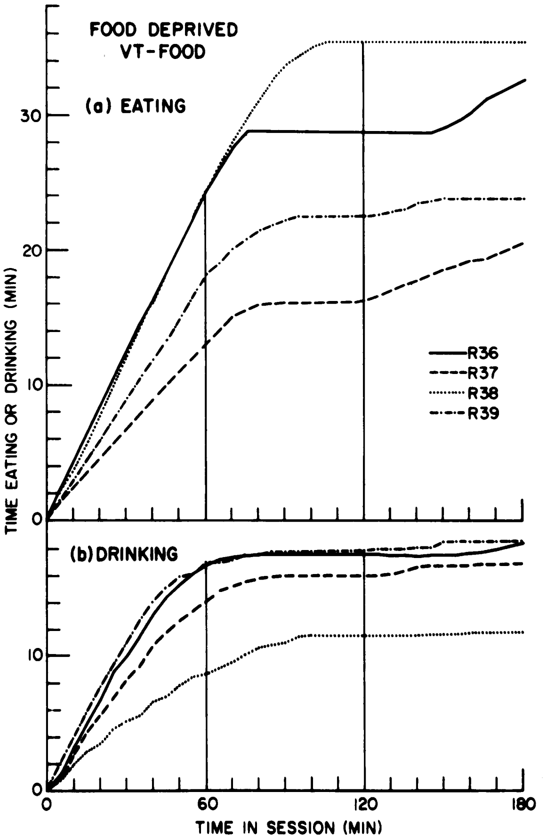

Fig. 4. Cumulative time spent (a) eating and (b) drinking by four food-deprived rats during a 3-hour session with water freely available and food delivered on a variable time (VT) 20-sec schedule.

about the same time consuming food plus water during VT-food sessions as during free-food sessions. It is clear from Figures 5 and 6 that although consumption as a whole was similar during the two phases, the distribution of consumption between food and water was vastly different. In the free-food phase, consumption consisted of much more eating and much less drinking than in the VT-food phase.

To determine the conversion factor from pellets to seconds spent eating, it was assumed that eating plus drinking occupied the entire first 5 min of the session. Thus, in Figure 6 the points at the first 5-min interval of the free-food curves are circled to indicate that they were set at 5 min of consumption. The remaining points were free to vary. The apparent compensation of reduced eating by increased drinking suggests that food and water may be, at least to some extent, substitutable. The possibility that schedule-induced poly-

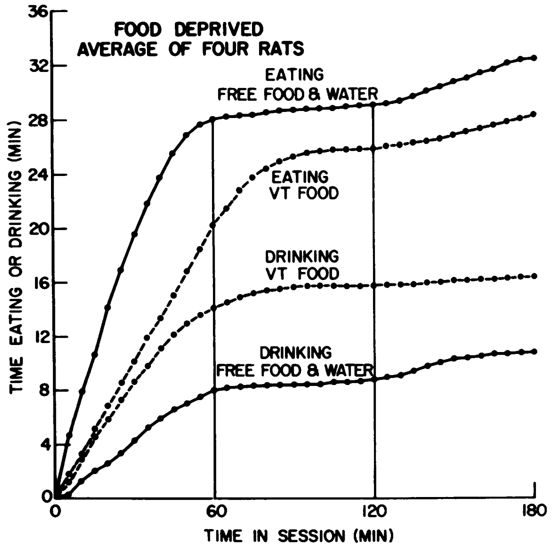

Fig. 5. Average cumulative curves of eating and drinking by four food-deprived rats during a 3-hour session with water freely available. Solid lines show data with food freely available. Dotted lines show data with food delivered on a VT 20-sec schedule.

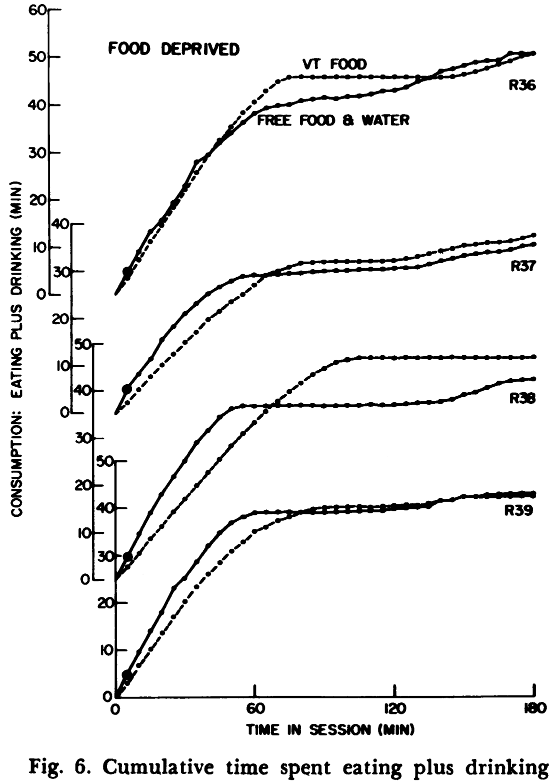

Fig. 6. Cumulative time spent eating plus drinking by four food-deprived rats during a 3-hour session with water freely available. Solid lines show data with food freely available. Dotted lines show data with food delivered on a VI 20-sec schedule.

dipsia may be an artifact of that substitutability will be discussed after we consider the results with water deprivation.

Food Deprivation: Massed-Reinforcer Control

All of the rats ate less during the VT-food phase than during the free-food-and-water phase. Thus, they had more time to drink during the VT. It is necessary to ascertain whether the extra time itself, as opposed to the delivery of food on a periodic schedule, was responsible for the extra drinking. A control for time of water availability would be simply to provide the amount of food freely (e.g., by putting it in a dish on the floor of the cage) that would ordinarily be consumed during the scheduled food delivery. This is called a massed-reinforcer control (Roper, 1981). The difference between the water consumed with scheduled food and the water consumed with massed food must, then, be due to the schedule itself rather than to the time available to drink. Such a control would not make sense in this experiment because the duration of the session is so long. By the end of the 3-hour session, schedule-induced polydipsia was no longer occurring. At that point a control for schedule induction would be meaningless. Instead, the point, *t*, during the session at which schedule-induced polydipsia ceased, was found as follows: At the beginning of the session, for a given amount of eating, each rat drank more during the VT schedule than it did for the same amount of eating during the crf schedule. But as the session progressed, drinking during the VT schedule eventually fell below drinking during crf. The time of the VT schedule at which drinking (for a given amount of eating) was equal during VT and crf was determined. This point, *t*, was assumed to be the limit of schedule-induced polydipsia for the purposes of this control procedure. At Point *t*, the amount (*k* pellets) of food consumed on the VT schedule was determined. Then, in the massed-control procedure, that amount of food was provided freely by (a crf schedule) and the rats were allowed *t* min to eat the food and drink. When *k* pellets had been consumed the lever was withdrawn, but the rats could drink for what remained of the *t* min. Table 1 shows the results. None of the rats drank as much with the massed reinforcers as with the same number of reinforcers delivered on the VT 20-sec schedule. The difference (*t* test, last 10 days) was significant at the .01 level for each of the four rats (including Rat 38: the small difference was highly reliable).

Table 1

Results of the massed-reinforcer control: food-deprivation phase.

Rat	t *min*	k *pellets*	*Drinking-VT (min)*	*Drinking-Control (min)*
36	60	271	16	4
37	105	318	16	10
38	45	159	7	6
39	60	138	17	7

This demonstrates that at least some drinking during the VT schedule was due to the periodic distribution of the food rather than to the extra time available for drinking or to the amount of food eaten.

Water Deprivation

Figures 7, 8, 9, and 10 correspond to Figures 3, 4, 5, and 6 but with water deprivation rather than food deprivation, and water instead of food delivered on a VT 20-sec sched-

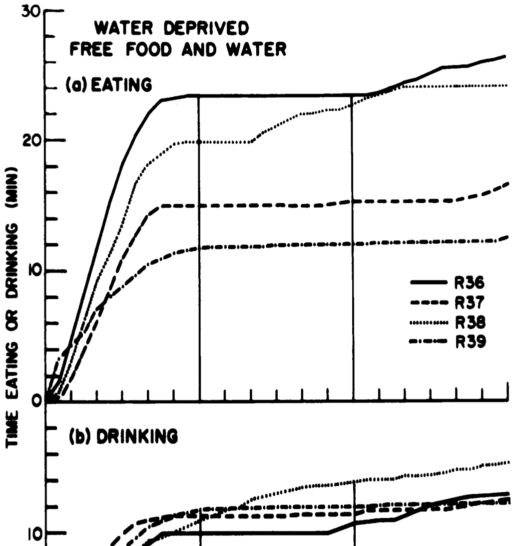

Fig. 7. Cumulative time spent (a) eating and (b) drinking by four water-deprived rats during a 3-hour session with free access to food and water (crf).

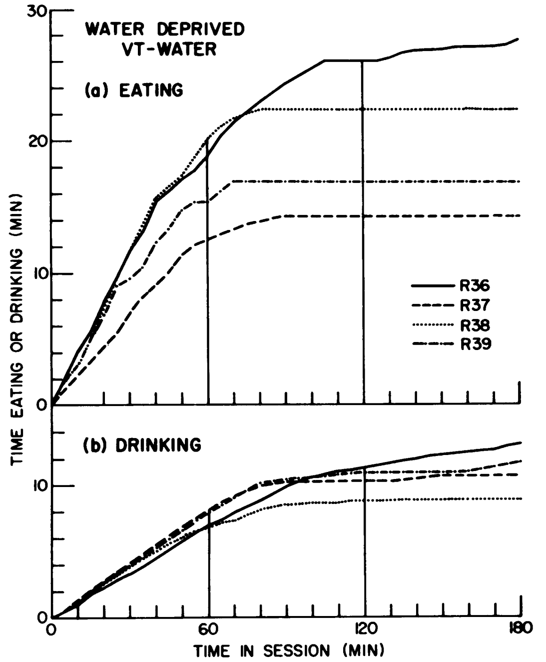

Fig. 8. Cumulative time spent (a) eating and (b) drinking by four water-deprived rats during a 3-hour session with food freely available and water delivered on a VT 20-sec schedule.

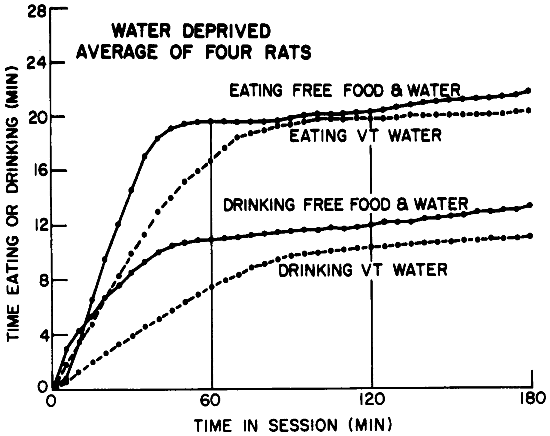

Fig. 9. Average cumulative curves of eating and drinking by four water-deprived rats during a 3-hour session with food freely available. Solid lines show data with water freely available. Dotted lines show data with water delivered on a VT 20-sec schedule.

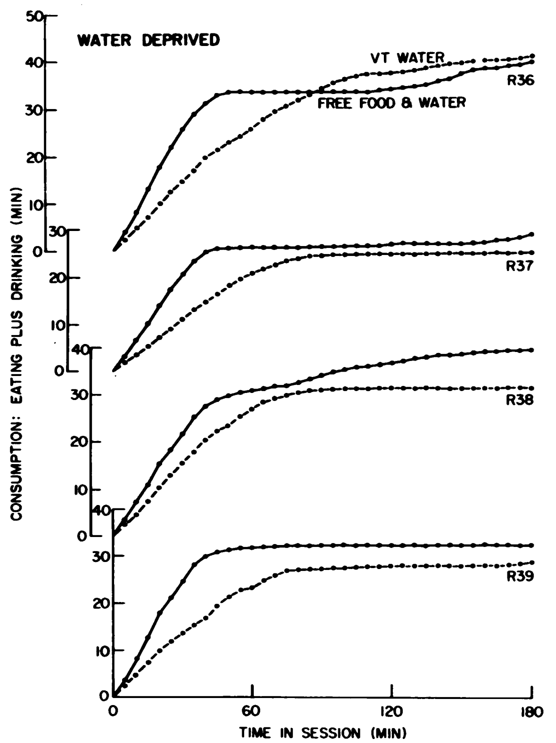

Fig. 10. Cumulative time spent eating plus drinking by four water-deprived rats during a 3-hour session with food freely available. Solid lines show data with water freely available. Dotted lines show data with water delivered on a VT 20-sec schedule.

ule. The results of the water-deprivation phase can be most easily understood by comparing them with the results of the food-deprivation phase. The pattern was similar for all rats, so we may compare the averages in Figures 5 and 9. The most obvious result was that the rats, regardless of whether they were food-deprived or water-deprived, spent more time eating than drinking (except for the first 10 min in the water deprivation condition). Of course these comparisons of eating and drinking depend on the conversion factors from licks and pellets to time drinking and eating. But the conversions would have to be off by a factor of 2 or more to reverse the order of eating and drinking in Figure 9.

Note next, in Figure 5, that the two VT curves (dotted lines) are bracketed by the free food and water curves (solid lines). This indicates that the food-deprived rats compensated for the lack of food during the VT-food phase by drinking more than they did with free food. A symmetric result in Figure 9 was not obtained. Water-deprived rats did not compensate for the lack of water in the VT-water phase by eating more than they did with free water. In fact, as can be seen in Figure 9, they ate slightly less on the average with VT water than with free water—the dotted lines do not bracket the solid lines. Figure 10 confirms this result. The total consumption (food plus water) was less during the VT-water phase than during the free-food-and-water phase for three of the four rats. As they did in the food-deprived condition, the rats persisted longer in consumption when the deprived commodity was provided on the VT schedule than they did when that commodity was provided freely. (The dotted curves of Figures 6 and 10 level off after the solid curves.) But only for Rat 36 did consumption persist long enough in the water-deprived condition to exceed consumption with freely delivered food and water. In this case (as in Figure 6) the adding of eating and drinking causes the shape of the functions to depend on the calculation of eating and drinking times from pellets and licks —which was to some extent arbitrary. However, for three rats, 37, 38, and 39, the dotted lines of Figure 10 would not have crossed the solid lines (but the dotted lines of Figure 6 would have crossed the solid lines) with any reasonable conversion factors.

Water Deprivation: Massed-Reinforcer Control

This control procedure mirrors the massed-reinforcer control procedure with food deprivation. At the beginning of the water-deprivation sessions (despite the apparent absence of schedule-induced polyphagia), for a given amount of drinking, the rats ate more food with VT 20-sec schedules of water than they did with crf (this will become clear when Figure 12 is discussed). The food eaten (per amount of water drunk) with crf increased and finally exceeded the food eaten with VT 20-sec. The time in the VT session at which this reversal occurred is shown in Table 2 in the column labeled *t* min. The number of licks made in the VT session at that point is shown in the column labeled *k* licks. The time spent eating during those *t* min is shown in the column labeled Eating VT. In the massed-reinforcer-control condition, each rat was allowed *k* licks, but freely rather than on a VT schedule. Then the drinking tube was withdrawn and the rat was allowed to eat for the remainder of the *t* min. The amount eaten under these conditions is shown in the column labeled Eating-Control. In no case was VT eating significantly greater (*t* test, last ten days: .01 level) than control eating. In one case (Rat 39) it was significantly less. Contrary to the results with food deprivation, the rats ate as much or more when water was massed (and additional time was provided to eat) as they did when the amount of water was provided periodically on a VT schedule. Any polyphagia measured (in a *t*-min session) can thus be attributed to the extra time available for eating when water is provided periodically rather than to the periodicity itself. The failure to find measurable polyphagia with the values of *t* used does not imply that there would have been a similar failure with briefer values of *t*. The massed-reinforcer control, although probably the best available control for schedule-induced phenomena (Roper, 1981), needs to be applied at several durations (values of *t*). Unfortunately, this is an outcome of the experiment rather than a fact we knew before we started.

Table 2

Results of the massed-reinforcer control: water-deprivation phase.

Rat	t *min*	k *licks*	*Eating VT (min)*	*Eating Control (min)*
36	40	1800	12	13
37	60	2900	13	11
38	50	2200	6	15
39	35	1800	8	11

DISCUSSION

Leisure

Considering the single lever press to obtain food as part of the food consummatory response (eating), three categories of behavior comprised a session in these experiments: eating, drinking, and all other behavior (leisure). Eating and drinking together comprised on the average only about 30 min of the first hour of the 3-hour sessions of Experiment 2, and during the remaining two hours not more than 10 additional minutes were spent by any rat eating and drinking. Thus, behavior other than eating and drinking comprised a significant fraction of the session. If one category is constrained (as by a VT schedule), the other two must fill in the gap. Of these other two activities, the one more substitutable for the constrained activity will tend to increase most. The degree to which any one of these categories of behavior is substitutable for another is thus important.

Because eating and drinking are strongly related, it is possible to describe these two categories of activity alone in terms of a modified form of the matching law (see Heyman & Bouzas, 1980) but the meaning of the parameters, the limitations of conformity to matching, and the changes in behavior over the course of an experimental session require consideration of the third category—leisure.

Choice and Physiological Constraints

It is possible to regard eating and drinking together as if the rat chose among the three categories in two stages: (1) consumption vs. other behavior and, if consumption is chosen, (2) food vs. water. According to certain theories of choice (e.g., Tversky & Sattath, 1979), all choices are made in this structured way. Figures 6 and 10 indicate that the first choice (consumption vs. leisure) cannot be wholly independent of the schedule of reinforcement. Even if we suppose that a rat chooses to consume, it may be unable to consume because of constraints both external and physiological. For instance, a thirsty rat may choose to consume food or water but water may be unavailable (external constraint), and although food is available, it may be physiologically impossible to eat more than a certain amount of food in a given state of water deprivation. The reverse, however, may not be true. In a given state of food deprivation, the rat may be capable, once having chosen to consume food or water, of substituting a great amount of drinking for the absent food. Thus schedule-induced polydipsia (and lack of schedule-induced polyphagia) may be said to be due to asymmetry of the physiology of eating and drinking of rats. Hungry rats may be able to drink a lot, but thirsty rats may not be able to eat a lot. We confirmed this by measuring home-cage consumption of nondeprived, food-deprived, and water-deprived rats.

Home-cage consumption was examined with three rats from Experiment 2 (the fourth had died). The rats were kept 24 hours per day in the experimental chamber, which served as the home cage (for six days: two at each condition). Food and water consumption of each rat was measured with no deprivation (food and water continuously available), with food deprivation (food lever available only 26 min per day which kept the rats about 80% of normal weight), and with water deprivation (water tube available only 11 min per day). On the average, the undeprived rats ate for 39 min and drank for 28 min each day. When food-deprived, they drank for 26 min each day, about equal to undeprived drinking. But when water deprived, the rats ate for only 24 min. Thus, although food deprivation can occur alone, water deprivation involves food deprivation as well.

Utility Function

Without denying the validity of the above analysis it is possible to express the same facts in more strictly economic terms and with somewhat better precision. First, the assumption that the rat makes a pair of binary choices can be expressed in terms of a utility function (suggested by Rachlin, 1982) as follows:

$$U = [aE^x + bD^x]^y + cL^y, \qquad (1)$$

where x is a measure of substitutability between eating (E) and drinking (D), and y is a measure of substitutability between consumption and leisure. Rachlin, Kagel, and Battalio (1980) demonstrated that this form of utility function (when combined with assumptions about how schedules of reinforcement constrain behavior, and the assumption that organisms maximize utility within those constraints) implies a generalized form of matching with concurrent schedules of food and water. The coefficients a and b determine the degree of bias in the matching equation for food-water choice, and the exponent x determines the sensitivity (Baum, 1974). Thus,

$$\frac{T_1}{T_2} = \frac{a}{b}\left(\frac{E}{D}\right)^x, \qquad (2)$$

where T_1 and T_2 represent time spent at instrumental responses upon which food and water are contingent. (See Appendix for derivation of Equation 2 from Equation 1.)

The experiments of Rachlin, Green, Kagel, and Battalio (1976) and Hursh (1978) suggest that $x < 0$. If $x < 0$ the term in the brackets of Equation 1 would vary inversely with E and D. To make the variation direct the term in brackets can be replaced by: $[-aE^x - bD^x]$, as is done later in Equation 3. A finding of $x < 0$ makes eating and drinking economic complements. In other words, the consumption of food and water represents a single drive system that requires both eating and drinking in a certain proportion rather than multiple drive systems that require one or the other. According to Halliday (1980, p. 212), "The fact that it is impossible to separate the kidney's functions as a controller of both metabolic waste-products and of body water surely casts doubt on the validity of any separation of feeding and drinking into separate systems."

With respect to the other exponent, y, Battalio, Kagel, and Green (1979) and Rachlin et al. (1981), in analyzing single-ratio and interval-schedule data as a choice between E and L, have found $0 < y < 1$. Consumption and leisure thus are not complements; nor are they completely substitutable. The three-way utility function (Equation 1) with $x < 0$ and $0 < y < 1$ predicts the sort of choice between eating, drinking, and leisure that might obtain between, say, bats, baseballs, and footballs. Bats and baseballs would be complements, and the two together would be substitutable (to some extent) for footballs.

Consumption Curves, Polydipsia, and Polyphagia

A complete economic analysis of the data of this experiment would treat both the leisure-consumption and the food-water choices and their interaction. Figure 11 shows consumption-leisure choice as a double-cumulative plot. These data were derived from Figures 6 and 10 by subtracting cumulative consumption at each 5-min interval from the time in the session during which the consumption occurred. The difference (L) was then averaged across rats and plotted against average consumption for the first 12 5-min intervals (the first hour) of the session. Figure 11 reveals clearly that the constraint (the VT schedule) reduced total consumption in both the food-deprived and water-deprived conditions. The reduction was strongest during the first hour of the session. For the remaining two hours (not shown in Figure 11), consumption was more nearly equal in the crf and VT 20-sec phases. This difference between crf and VT 20-sec consumption curves considerably complicates an economic analysis because it implies that by treating the consumption-leisure and the food-water choices separately, we ignore a significant and possibly important interaction.

Nevertheless, for illustrative purposes it may be worth examining the food-water choice in isolation. Figure 12 shows this choice in terms of double cumulative plots of eating time vs. drinking time, averaged across rats for the first hour of the session (consumption was considerably reduced during the next two hours). The two conditions (food and water deprivation) and the two phases within each condition (crf and VT 20-sec) are plotted separately.

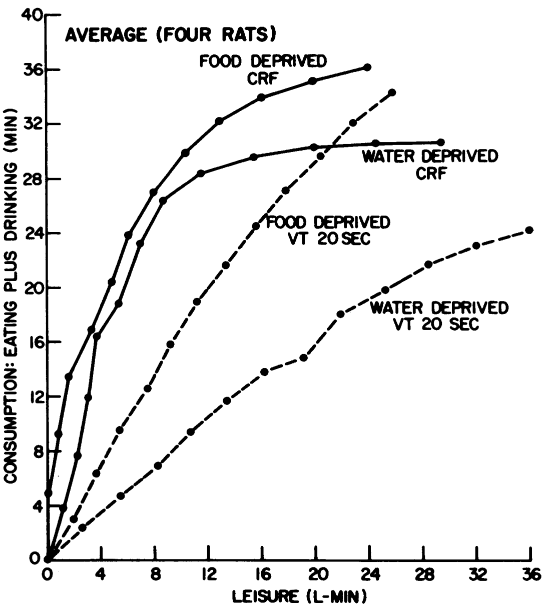

Fig. 11. Average cumulative curves of eating plus drinking as a function of other behavior (leisure). Solid lines show data of rats with food and water freely available. Dotted lines show data of rats with food or water delivered on a VT 20-sec schedule.

In the top panel imagine a line drawn perpendicular to the x-axis at any point along it. The difference between the two curves along this line is "excess drinking" for a given amount of eating. The height of the VT 20-sec consumption curve above the crf consumption curve reveals that for a given amount of eating the food-deprived rats drank much more during the VT 20-sec schedules than during crf. This is a measure of schedule-induced polydipsia.

Now, in the bottom panel of Figure 12, imagine a line drawn perpendicular to the y-axis at any point along it. The difference between the two curves along this line is "excess eating" for a given amount of drinking—the horizontal separation of the VT 20-sec consumption curve from the crf curve. This means that for a given amount of drinking

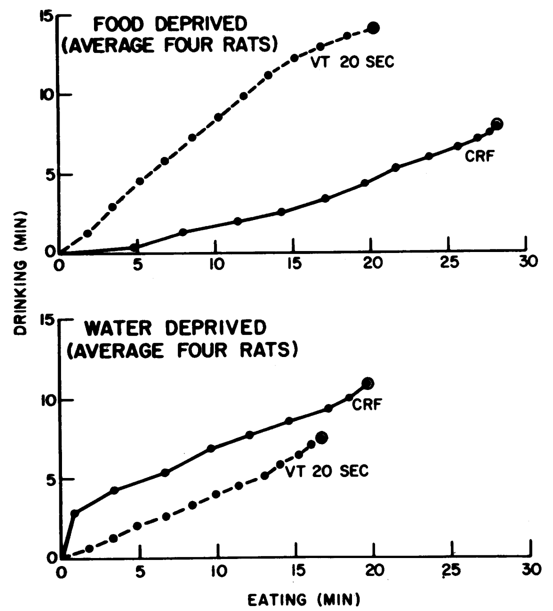

Fig. 12. Cumulative curves of drinking vs. eating (consumption curves) averaged across four rats (a) food deprived and (b) water deprived. The solid lines show data with food and water freely available (crf). The dotted lines show data with (a) food and (b) water delivered on a VT 20-sec schedule.

the water-deprived rats ate more during VT 20-sec water than during crf. This horizontal displacement occurred in the individual consumption curves of each of the rats. It represents evidence for polyphagia symmetrical to the commonly obtained polydipsia. If what is meant by schedule-induced polydipsia is drinking during schedule-delivered food in excess of drinking with consumption of that same amount of freely available food, then Figure 12 shows a symmetrical schedule-induced polyphagia (eating during schedule-delivered water in excess of eating with consumption of that same amount of freely available water). But the massed-control procedure (see Tables 1 and 2) indicates that although the polydipsia is not an artifact of the extra time available to drink during the VT 20-sec food schedule, the polyphagia may well be an artifact of the extra time available to eat during the VT 20-sec water schedule. As mentioned previously, however, the occurrence of "genuine" schedule-induced polyphagia cannot be rejected on the basis of a single massed-reinforcer control. Massed-reinforcer controls need to be run at shorter durations. It may well be that previous failures to find schedule-induced polyphagia or other schedule-induced activities (Roper, 1981) result from too-long session durations. Figure 12 indicates that the maximum polyphagic effect, if it occurs, takes place near the beginning of the session.

Absolute and Relative Consumption Space

The double cumulative curves of Figures 11 and 12 are useful for economic analysis because they occupy the same space as the utility function specified by Equation 1. The space defined by these axes may be called consumption space and the curves, consumption curves (Rachlin, 1982). Before the curves can be compared to what Equation 1 would predict, a distinction needs to be made between absolute and relative consumption space. Equation 2 defines an absolute space but the curves of Figures 11 and 12 start at points in that space arbitrarily determined by the home-cage conditions of deprivation. Figures 11 and 12 put a food-deprived rat and a water-deprived rat at the same point (the origin—the beginning of the session), but a food-deprived rat "has" more water than a water-deprived rat and a water-deprived rat "has" more food than a food-deprived rat.[1] A food-deprived and a water-deprived rat are equivalent, not at the beginning of the session, but at the end of the session with crf when both have eaten and drunk to satiation. In absolute space, then, crf consumption curves are more meaningfully joined at their termination than at their origin, but the points of the VT 20-sec consumption functions of food-deprived and water-deprived rats have the same origins as their corresponding crf functions.

Figure 13 shows this transformation for the points of the crf functions of Figure 12. The circles and triangles in the figure represent averages of four rats. The solid lines are theoretical curves, to be derived below.

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[1] A feature of the analysis is the fact that it seems to ignore depletion of food and water during the session. As Rachlin (1982) pointed out, a utility function such as Equation 1 that contains no maximum (bliss) point may be used to describe consumption curves from which depletion has not been subtracted. If we were to attempt to account for depletion, as the model of Houston and McFarland (1980) does, the utility function would have to be changed. The methods for converting from a nondepletion to a depletion model have not, to our knowledge, been worked out.

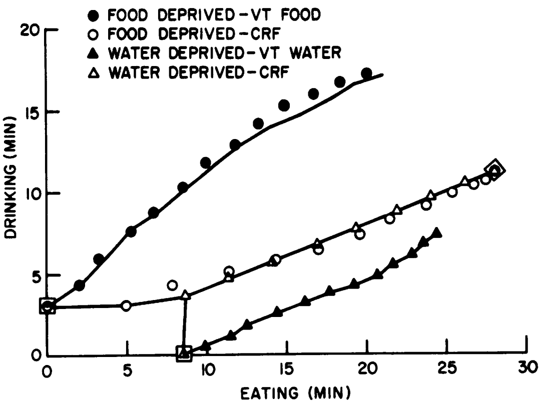

Fig. 13. The consumption curves of Figure 12 combined on a single set of axes. The ends of the solid lines of Figure 12 are joined at the diamond-enclosed point. The circles and triangles represent the data of Figure 12. The origin of this figure was determined by extending the asymptote of the unfilled diamonds and circles downward to the left until it intersected a vertical line drawn through the leftmost (square-enclosed) circle. The solid lines represent theoretical consumption curves derived as shown in subsequent figures.

In Figure 13 the top and bottom panels of Figure 12 are superimposed. The superimposition is keyed, not at the origin of the axes but at the end of the crf functions (the circled points at the end of the solid lines of Figure 12). In Figure 13 the superimposed points are enclosed by a diamond. Thus, the origins of the upper and lower panels of Figure 12 are not superimposed in Figure 13. The two points of origin are enclosed by squares in Figure 13. The axes of Figure 13 were constructed as follows: First, a vertical line was drawn through the common origin of the food-deprived consumption functions. This is the vertical axis of Figure 13. Then a straight line was projected from the diamond-enclosed point along the common line formed by the two crf functions (the unfilled circles and triangles) until it intersected the ordinate. This intersection is the origin of Figure 13. Then a horizontal line was drawn through the origin. This is the horizontal axis. In Figure 13 the horizontal axis runs through the square-enclosed point representing the common origin of the water-deprived consumption curves but this is a coincidence. The functions of individual rats of Figure 14 (constructed in the same way as Figure 13) have the horizontal axis near but not intersecting the origin of the water-deprived consumption functions. The axes of Figure 13, constructed in this way, are not true absolute scales. However, they indicate the relative starting points of hungry and thirsty rats in absolute consumption space. Hungry (food deprived) rats start the session with some water (above the origin of Figures 13 and 14) and thirsty (water deprived) rats start the session with some food (to the right of the origin). The low slope of the common (food and water deprived) crf consumption

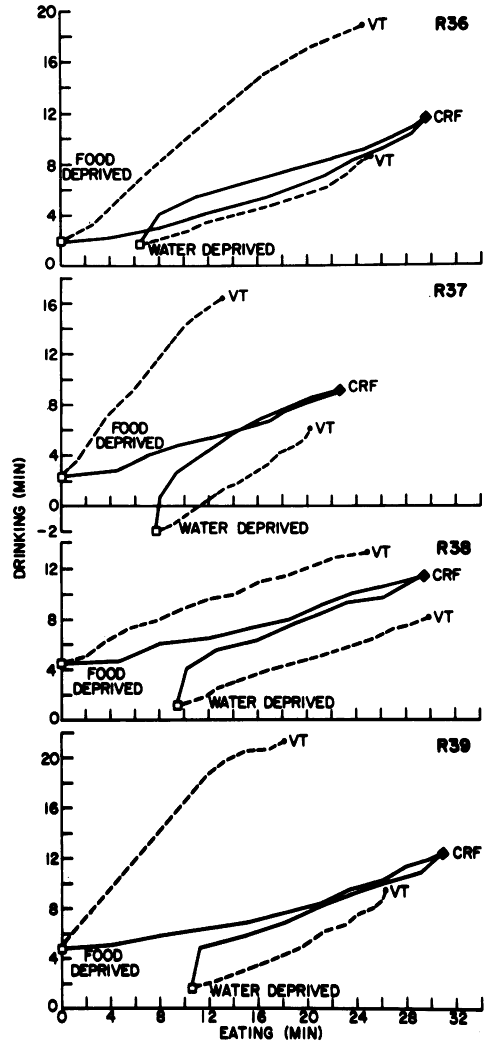

Fig. 14. Individual consumption curves of four rats constructed as was the average consumption curve of Figure 13. In this figure the solid lines represent data with food and water freely available. The upper dotted line represents data of food-deprived rats with food delivered on a VT 20-sec schedule. The lower dotted line represents data of water-deprived rats with water delivered on a VT 20-sec schedule.

curves reflects the fact that, at stability, rats spend more than twice as much time eating as they spend drinking. All water-deprived rats made up for their deprivation (reached asymptote) within 5 min of crf, whereas food-deprived rats took about 10 min on the average to reach the common line. This occurred despite the fact that water-deprived rats were also somewhat food deprived.

The assumptions behind the overlapping of points in Figure 13 are: (1) Rats with the same home-cage deprivation conditions begin experimental sessions at the same point in absolute consumption space, and (2) rats with the same experimental conditions will be (within 60 min) at the same point in absolute consumption space. The squares at the bottom of the curves represent the first assumption. The diamond at the end of the crf consumption curves represents the second assumption. The solid lines of Figure 14 are crf consumption curves joined at the diamond. The solid line curving downwards represents the water-deprived condition. The upper and lower dotted lines are consumption curves from the VT 20-sec food and VT 20-sec water phases. As in Figure 13 the ordinate was drawn through the box-enclosed point representing the starting point for the food-deprived condition. The origin is at the intersection of the ordinate with a line of slope .4 (the slope of the line fitted to the average data in Figure 13) drawn through the diamond-enclosed point.

Note the wider space, generally, between the VT food and crf consumption curves of food-deprived rats than between the VT water and crf consumption curves of water-deprived rats. This asymmetry represents the finding of a high degree of schedule-induced polydipsia as opposed to little or no schedule-induced polyphagia. The functions of Figures 13 and 14 thus represent quantitatively what is often considered to be a qualitative, physiological difference. We will now show (for the average functions of Figure 13) how an economic analysis in terms of constraints and utility functions may throw light on this difference.

Constraints

Figure 15 shows the constraints that apply over a 5-min period for the three schedules used in Experiment 2: crf, VT 20-sec food, and VT 20-sec water. The crf constraint allows the subject to eat or drink (or both) for the entire 5-min period. Consumption can thus occur anywhere within the triangle. The diagonal represents totals of eating-time plus drinking-time of 5 min. The VT 20-sec food schedule restricts eating further within the crf constraint. The average obtained eating time for the first 5 min of the VT 20-sec food schedule was 1.75 min. We assume that this is a limit beyond which eating could not occur. Thus the VT 20-sec food schedule confines consumption to the shaded area bounded by the vertical line and the ordinate of Figure 15. Similarly, the VT 20-sec water schedule confines consumption to the shaded area bounded by the horizontal line and the abscissa of Figure 15. At the beginning of the session these schedule constraints were real constraints because, with crf, the rats ate and drank much more than these amounts.

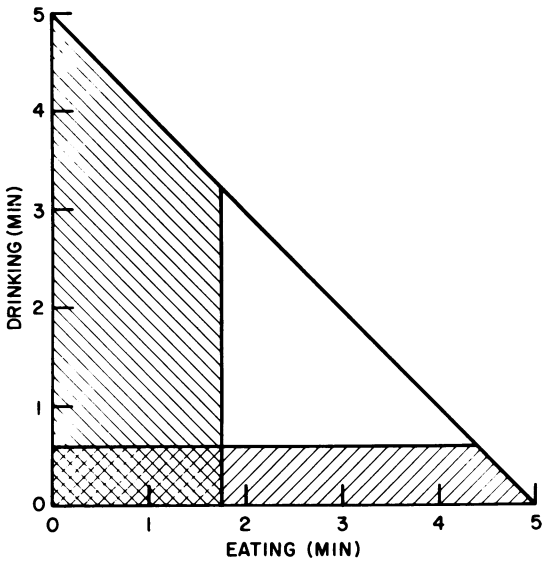

Fig. 15. Constraints of Experiment 2. The area within the triangle defined by the axes with the 45° line represents the limits of eating and drinking that can occur within a 5-min period with both food and water freely available. The shaded area within the triangle bounded by the vertical line and the ordinate represents the eating and drinking that can occur within 5 min with food delivered on a VT 20-sec schedule. The shaded area within the triangle bounded by the horizontal line and the abscissa represents the eating and drinking that can occur within 5 min with water delivered on a VT 20-sec schedule.

Recall that a critical assumption for this analysis is that food-water choice is independent of leisure-consumption choice. As the session progresses and leisure occupies greater fractions of the 5-min intervals, less time is therefore available for eating and drinking, and the triangle shrinks. That is, the diagonal line moves downward and to the left towards the origin. Eventually, with both VT-food and VT-water schedules, it can move wholly within the shaded area. Thus, when rats become satiated and leisure occupies most of the time, a VT 20-sec schedule would be equivalent to crf. That is, at sufficiently low response rates, a VT 20-sec schedule equals crf in terms of reinforcement rate.

Maximization

Maximization theory assumes that, within the constraints imposed by a schedule, organisms maximize utility (given by a utility function such as Equation 1). In fitting Equation 1 to the data of Experiment 2, we first assume the value of leisure is irrelevant as regards choice between food and water and then, for convenience, that $x = -1$.

$$U = \left[-\frac{a}{E} - \frac{b}{D} \right]. \quad (3)$$

If $x = -1$ fails to fit the data, other values of x can be explored. (It will soon be clear that this is not necessary.) U is made negative in Equation 3 so that increasing values of E and D will increase U. The dotted lines of Figures 16 and 17 show Equation 3 with various values of U and $a/b = 6.25$. These lines, each at a constant utility, are called indifference curves. The relative values of a and b were determined as follows. The crf consumption functions of Figure 13 quickly reach an asymptotic slope, $D/E = .4$. Maximization of utility with crf consumption is at the point where the utility function (given by Equation 3) is tangent to the 45° diagonal constraint line (of Figure 15). For Equation 3 this occurs when:

$$\frac{\partial U}{\partial E} = \frac{\partial U}{\partial D},$$

$$-aE^{-2} = -bD^{-2}, \text{ and}$$

$$\frac{a}{b} = \left(\frac{D}{E}\right)^{-2} = (.4)^{-2} = 6.25.$$

The starting point of the crf consumption curve for food-deprived rats was taken from Figure 13. The curve was constructed by first drawing the crf constraint triangle at the point where the consumption curve of Figure 13 intersects the D-axis. This is the lower left complete right triangle of Figure 16. The hypotenuse of this triangle is not tangent to any dotted line (indifference function). Instead, the maximum utility is reached at a corner of the triangle (shown as a plus-sign cross).

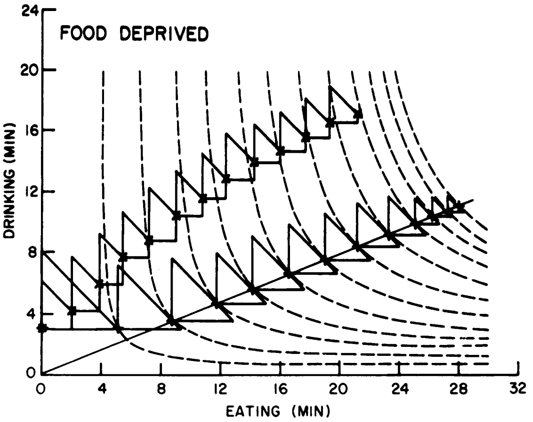

Fig. 16. Maximization of utility (Equation 3; $a/b = 6.25$) determined for the average of four food-deprived rats with constraints imposed by crf (triangles) and VT 20-sec (trapezoids) schedules of food. The triangle and trapezoid representing the initial 5-min period with each schedule are placed at a point on the ordinate where the food-deprived consumption curves of Figure 13 begin. Each dotted line is the maximum constant utility contour attainable within each triangular constraint. Except for the first, each dotted line is tangent to the hypotenuse of a triangle. Within the trapezoids, the highest attainable constant utility contour is always at the obtuse corner. Successive triangles and trapezoids are placed at the maximization points of earlier ones. Later ones are smaller because leisure (behavior other than eating or drinking) takes up more of each 5-min period as the session progresses. The upright and diagonal crosses are loci of maxima. They represent consumption paths that maximize utility.

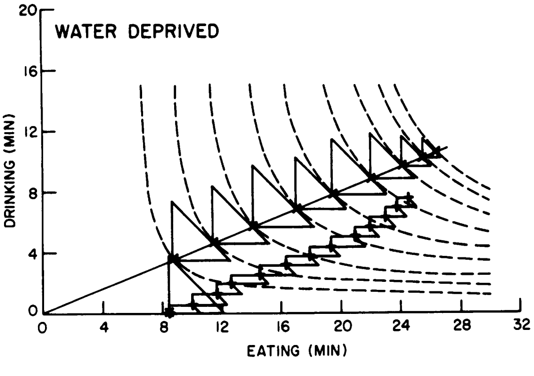

Fig. 17. Maximization of utility (Equation 3; $a/b = 6.25$) determined for the average of four water-deprived rats. The loci of upright and diagonal crosses, determined as in Figure 16, represent consumption paths that maximize utility for crf and VT 20-sec schedules of water delivery.

Then another complete right triangle (slightly smaller than the first, because some leisure occupied the second 5-min period) was constructed at the maximization point of the first. The hypotenuse of this second triangle was tangent to an indifference contour near its lower right corner. Subsequent triangles were constructed in the same way. The crf consumption curve for food-deprived rats is the locus of these maximization points and is drawn as a solid line in Figure 13. Then the VT 20-sec consumption curve for food-deprived rats was constructed in the same way. Note that in this case maximization was always at the corner of the truncated right triangle that represents the VT 20-sec constraint (shown as a multiplication-sign cross) because that point, of all points within the constraint-trapezoid, touches the highest indifference contour. This would be true with any indifference contours with slope more negative than -1 at that point. Thus the locus of VT 20-sec points depends not on the indifference functions per se, but on the constraint. That is, the elevation of the VT 20-sec consumption curve above the crf consumption curve (which is responsible for measured schedule-induced polydipsia) does not depend directly on the substitutability between food and water, on the value of x in Equation 3, or on the form of Equation 3 itself. A number of utility functions common in economics (Newman, 1965) would have done as well.

The "theoretical" consumption curve constructed from the trapezoids is largely an artifact of the constraints. The assumption that the food-water choice is independent of leisure (shrinking the trapezoids by the amount of leisure taken) hardly affects the shape of the theoretical consumption curve. It would have been about the same, even if the trapezoids had remained at the initial size (which was determined by the schedules). The space between the VT consumption curve and the crf consumption curve—the space that causes the appearance of schedule-induced polydipsia—is almost wholly due to the crf consumption curve, which is free to take on any angle. If the crf curve were raised, schedule-induced polydipsia would not have been found. If the crf curve were lowered, schedule-induced polydipsia would have been greater. The VT consumption curve, given the schedule, is relatively fixed. When it is said that rats drink "excessively" during a VT schedule, one must ask: Compared to what? If it be an anomaly at all, schedule-induced polydipsia is as much an anomaly of baseline behavior (behavior with food and water freely available) as it is of schedule induction.

Figure 17 shows the same curve-fitting process as Figure 16 with the same set of indifference functions, but with a new starting point, in absolute consumption space, representing water deprivation, and a new set of constraint functions representing VT 20-sec water schedules. These "theoretical" functions are drawn in Figure 13 as solid lines. They fit the data (the circles and triangles) quite closely.

It may be instructive now to review some of the assumptions that were necessary and, perhaps more importantly, those that were unnecessary in constructing the consumption curves of Figures 16 and 17. First, indifference functions with particular substitutabilities need not be specified. Two aspects of the indifference functions that were important to the shape of the consumption curves were their negative slope and their homotheticity—the fact that the points of tangency to parallel lines form a straight line drawn from the origin. This property is responsible for the straight asymptote of the crf consumption curves. (Homotheticity was shown by Rachlin et al. [1980] to be a requirement for indifference functions if the matching law of Equation 2 were to imply maximization.)

The relationship between the constants a and b provided the asymmetry in the space between the food-deprived and water-deprived VT 20-sec functions and the crf function that resulted in polydipsia and lack of obtained polyphagia. Referring to Equation 2 it may be possible to determine which of the two consummatory responses could be induced by scheduled presentation of the other by examining bias with concurrent schedules.

The 5-min temporal-integration period (the size of the triangles) assumed in constructing the consumption curves was not critical. An infinitely small integration period would have reduced the size of the triangles proportionally and produced the same consumption curves as in Figure 13 for both crf and VT 20-sec schedules.

For a given crf curve, the difference between a VT and crf curve (the difference between the locus of the xs and that of the $+$s) is due to the shape of the constraints. The VT constraint is a triangle with (so to speak) a piece cut off. The missing piece of the triangle contains what would have been the point of tangency between the triangle and the indifference contour. Thus the VT schedule forbids the sort of equilibrium that obtains under crf (the constraints for which are complete triangles). The trapezoids that result from cutting off the corners of triangles are nowhere (in Figures 16 or 17) tangent to indifference contours. Instead, the highest indifference contours are reached at the obtuse corners of the trapezoids (where the *x*s are). A schedule less rich than that used (say a VT 1-min instead of VT 20-sec schedule) would make the trapezoids proportionally thinner (by cutting off a bigger piece of the triangle). It can be seen from Figures 16 and 17 that thinner trapezoids would force the consumption curves further away from the curves formed by complete triangles (the crf curves). Thus, the constraint imposed by VT schedules tends to force consumption curves away from those obtained with crf schedules.

But constraint interacts with bias (a/b). The low slope of the asymptote of the crf consumption curve of Figures 16 and 17 leaves less room below it than above it. Even though the VT water constraint was narrower than the VT food constraint (see Figure 15), the fact that the bias provided little room below the crf curve of Figure 17 indicates that the VT water constraint may not have been narrow enough to force the curves apart. This suggests that still less-dense schedules of water might increase the likelihood of schedule-induced polyphagia.

A most critical assumption was the low but positive substitutability between food and water on the one hand and leisure on the other (the exponent y). This assumption allowed us to consider food-water choice after leisure was, in effect, subtracted out. That is, it allowed us to consider choice among food, water, and leisure as Tversky and Sattath (1979) suggest all choices be considered—as a tree-structure of decisions. In this case, the sequence is (1) consumption vs. leisure, (2) food vs. water. This choice structure implies a commitment (Rachlin & Green, 1972). Once the rat decides to consume, the choice of leisure is out of consideration. If the second decision is to eat and eating is unavailable, the rat drinks. The rigidity gives rise to schedule-induced polydipsia. Its failure to give rise to a symmetric schedule-induced polyphagia is due, in terms of this model, to the bias (the relative values of a and b in Equation 3). That is, a little water is worth a lot of food (2.5 times as much, according to Equation 3).

We are still a long way from being able to make predictions about schedule-induced phenomena in general. We do not know the limits of the relationships between x and y and between a and b in Equation 3 that would and would not result in a schedule-induced effect. If these limits were known, it would still be necessary to discover what consummatory activities fit within their range.

Methods for deriving the parameters (a, b, x, y) of the utility equation from the parameters of the matching equation are suggested in Rachlin et al. (1980). With this interpretation of matching, concurrent schedules could be used to investigate the limits of schedule-induced phenomena. The rarity of such phenomena (Roper, 1981) suggests that these limits may be narrow.

CONCLUSIONS

All this is not to say that eating and drinking are not biological phenomena. They are biological phenomena and may be analyzed in purely physiological terms—as interactions among the central nervous system and various boldily organs. Nevertheless, like other biological phenomena, they are also economic phenomena and may be analyzed, as we have done here, in purely economic terms.

Apparent anomalies such as schedule-induced polydipsia are not properly "limits of learning" or "limits of instrumental or operant conditioning" or evidence contradictory to a "general process theory of behavior." When the parameters of a general process theory, such as the economic theory described here, are varied symmetrically over a wide range, not limited by custom or historical accident, schedule-induced polydipsia may be seen in terms of those parameters.

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APPENDIX

According to Equation 1, with concurrent schedules of two commodities (ignoring leisure):

$$U = aE^x + bD^x.$$

If the schedules are ratio schedules, the amounts E and D are fixed ratios (r_1 and r_2) of the times spent at the respective instrumental responses (T_1 and T_2). Thus, the feedback functions are:

$$E = r_1 T_1;\ D = r_2 T_2, \text{ and}$$

$$U = a(r_1 T_1)^x + b(r_2 t_2)^x.$$

Setting the partial derivatives of U with respect to T_1 and T_2 equal to each other (maximizing):

$$a\, r_1^x\, T_1^{x-1} = b\, r_2^x\, T_2^{x-1}.$$

Substituting and rearranging terms:

$$\frac{T_1}{T_2} = \frac{a}{b}\left(\frac{E}{D}\right)^x.$$

A corresponding analysis for interval schedules depends on the feedback function. If the feedback functions are $E = r_1 T_1^m$ and $D = r_2 T_2^m$, maximizing still implies matching. Although there has been considerable debate as to the precise feedback function appropriate for interval schedules (Nevin & Baum, 1980), the form of all proposed functions is more or less approximated by the above with $m \simeq .1$.