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LICK-TRADING BY RATS: ON THE SUBSTITUTABILITY OF DRY, WATER, AND SACCHARIN TUBES

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Thirsty rats licked two metal tubes: a water tube paired with another water tube, with saccharin, or with a dry tube. For each pair, a multipoint baseline function was measured by offering free access to one tube throughout each session, and free or restricted access to the other. The three resulting baseline functions showed the members of each pair to be mutual substitutes: When access to either tube was restricted, the rats made more licks at the other. A linear function identified the two water tubes as perfect substitutes. Convex functions identified the members of the saccharin-water and the dry-water pair as imperfect substitutes. Each pair was also tested under several reciprocal fixed-ratio schedules that required instrumental licking of either tube for contingent access to the other. The resulting schedule functions showed the members of each pair to be perfect substitutes: Water licks decreased linearly as licks at the other water tube, the saccharin, or the dry tube increased, in agreement with a conservation model of instrumental performance. Baseline and schedule functions, indistinguishable in the water-water pair, indicated a schedule facilitation of dry-tube licking in the dry-water pair and of water-tube licking in the saccharin-water pair.

Key words: substitution, behavioral economics, noncontingent restriction, fixed-ratio schedules, conservation, elasticity, open economy, licking, rats

Although some still find it strange, many theorists have embraced the notion, now more than a decade old, that we cannot comprehend the effects of a contingency schedule without some knowledge of how the organism behaves when free of schedule constraints (Allison, 1976, 1980, 1981a, 1981b, 1982; Allison, Miller, & Wozny, 1979; Allison & Timberlake, 1973, 1975; Eisenberger, Karpman, & Trattner, 1967; Heth & Warren, 1978; Konarski, Crowell, Johnson, & Whitman, 1982; Lea, 1983; Podsakoff, 1982; Premack, 1965; Rachlin, Battalio, Kagel, & Green, 1981; Rachlin & Burkhard, 1978; Staddon, 1979; Timberlake, 1979, 1980; Timberlake & Allison, 1974). Contingency schedules normally specify two distinct types of behavior, such as pressing a lever and eating. Accordingly, those theorists have given much attention to the ***paired basepoint***, the total amount of each of the two activities performed without constraint under the ***paired baseline condition***, an experimental arrangement that makes each activity freely available for the duration of the test session. Thus, if a schedule session will require instrumental pressing of the lever for each contingent access to food, then a paired baseline session will make both lever and food freely accessible throughout.

We acknowledge the importance of the paired basepoint in theory, fact, and history. But some promising new possibilities become evident if one imagines the paired basepoint as only one among many other points on an entire baseline function (Allison, 1983, pp. 178-188). The present report describes measurements of three multipoint baseline func-

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tions, one function for each of three different behavioral pairs in the rat. In one pair the rat could lick two water tubes in different locations, one tube toward the left side of a wall, the other toward the center. Another pair combined the center water tube with a saccharin tube on the left; the third combined the center water tube with a dry tube on the left. We shall explore an economic interpretation that relates the shape of the baseline function to the intrinsic substitutability of one type of behavior for the other. Finally, we shall show that the individual's performance of the same two types of behavior under the constraints of several contingency schedules measures a comparable schedule function that may differ from the baseline function. A similar approach has been proposed by Rachlin et al. (1981).

Figure 1 illustrates both the procedure we followed in measuring the baseline functions, and a hypothetical function that one might expect to see with some behavioral pairs. The two axes represent the totals recorded for two types of behavior, *x* and *y*, over the course of a session with some fixed duration. The two broken lines intersect at the paired basepoint. If the axes represented licks at two different tubes, the paired basepoint would show that when both were freely available, the animal made twice as many licks at Tube *x* as at Tube *y*—4*a* licks at *x* and only 2*a* at *y*.

On the two axes themselves appear the two *single basepoints*, each one recorded under the *single baseline condition*—a condition that allows free access to one of the two activities, but no chance to engage in the other activity (Allison & Timberlake, 1974). The two single basepoints in the figure would show that when either tube remained freely available throughout, with the other absent, the animal directed the same number of licks at the one available tube—6*a* at Tube *x* and 6*a* at *y*.

The two remaining points in the figure help reveal the true shape of our hypothetical baseline function. We measure each of those two by resorting to a third kind of baseline condition that is both more restrictive than the paired and less restrictive than the single. We call this third one the *paired-single condition*, a term that reflects the condition's sequential structure. A paired-single session would start with the presentation of both tubes, just as in a conventional paired baseline session. But upon a prescribed number of licks at a prescribed tube (e.g., 100 licks at the tube on the left), the session would become the same as a conventional single baseline session: That tube would retreat, but the other would stay freely available throughout the rest of the session. Thus, the paired-single starts as a paired, but may change into and end as a single baseline session. Earlier investigators have called this the "massed baseline" condition (Timberlake & Wozny, 1979). Roper (1981) has advocated a similar "massed-reinforcer" baseline for the evaluation of various schedule-induced phenomena, such as schedule-induced polydipsia.

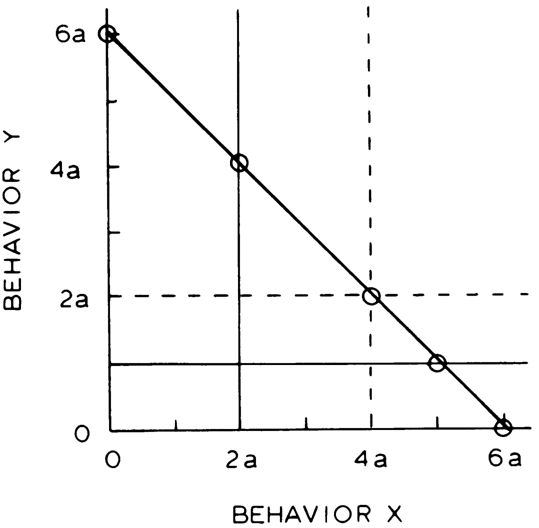

Fig. 1. Hypothetical measurement of paired, single, and paired-single basepoints, illustrating the two types of behavior as perfect mutual substitutes.

The paired basepoint gives the experimenter some needed guidance on two practical questions about the paired-single session: which tube to withdraw, and when? For example, the paired basepoint in the figure shows that in the paired condition, the animal made 4*a* licks at Tube *x*. We therefore have good reason to expect that if we start another session of the same duration by presenting both tubes, the animal will probably make half of that number, 2*a* licks at Tube *x*, before the session expires. It would probably be fruitless to expect appreciably more than 4*a* licks, although we might wait for more than 4*a* licks as a reliability check on the paired basepoint. Accordingly, we measure the second basepoint from the left by presenting both tubes; upon 2*a* licks at Tube *x*, we withdraw that tube but leave Tube *y* in place; when the session ends, we note that the animal has performed not only 2*a* licks at the restricted Tube *x*, but also 4*a* licks at the free Tube *y*. Thus, when we held Behavior *x* below its paired basepoint, Behavior *y* rose above its paired basepoint. And the greater the restriction on Behavior *x*, the greater the rise in the free Behavior *y* (compare the three leftmost points). If we thought it wise to measure more points on the function, we might run more paired-single sessions in which we restrict the animal to *a* licks at Tube *x*, 3*a* licks, and so forth, in a systematic bisection procedure.

The paired basepoint of Behavior *y* is 2*a* licks, perhaps sufficiently greater than zero to make it practicable to measure the effect of restricting Behavior *y* in a paired-single session. The effect of that restriction is illustrated by the fourth point from the left. Again we begin our paired-single baseline session by presenting both tubes; upon *a* licks at Tube *y*, we withdraw *y* but not *x*; and we find at the end of the session that the animal has registered not only *a* licks at the restricted Tube *y*, but also 5*a* at the free Tube *x*. Thus, when we held Behavior *y* below its paired basepoint, Behavior *x* rose above its paired basepoint—a rise directly related to the amount of the restriction (compare the three rightmost points).

The baseline function in Figure 1 is the fitted line that slopes downward through the five basepoints. Its downward slope suggests that those two particular types of behavior act as mutual substitutes in the economic sense: They move in opposite directions, each rising as the other falls, like the consumption of coffee and tea in the human economy. They do not function as complements—rising and falling together, like the consumption of flour and shortening—or as independents, which show no covariation.

Further, the linear relation between the two types of behavior would mark them as "perfect" substitutes, like paper dollars and silver dollars, or nickels and dimes: Presumably we are prepared to trade one of *y* in return for one of *x* ($y = b - x$), or two of *y* for one of *x* ($y = b - 2x$), no matter how much of *y* we happen to have at the time.

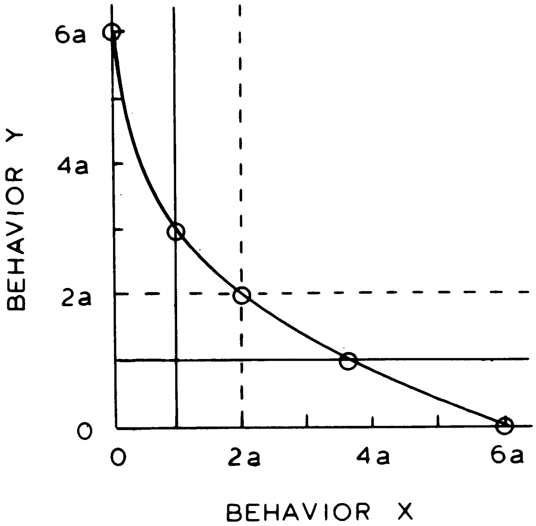

Fig. 2. Hypothetical measurement of paired, single, and paired-single basepoints, illustrating the two types of behavior as imperfect mutual substitutes.

In contrast, Figure 2 shows a baseline function that would tend to identify the two types of behavior as "imperfect" substitutes. The function is convex when viewed from the origin, like the relation often assumed for such supposedly imperfect substitutes as apples and oranges. The number of apples we are willing to trade in return for one orange depends on the number of each fruit we happen to have already. Having many apples but few oranges, we are willing to trade many apples for one orange. But having hardly any apples and many oranges, we are willing to part with fewer of our precious apples just to add one more orange to our already ample supply of oranges. A concave function would also identify imperfect substitutes.

We presume that the baseline function reflects intrinsic relations between the two types of behavior. We presume too that a schedule function, measured over a comparable portion of the bivariate space, may reveal some extrinsic change in the baseline relations.

Equally important, the baseline function may lead to different conclusions about schedule effects than any one point on the function, such as the paired basepoint. A simple example appears in Figure 3. The two solid lines radiating from the origin represent the constraints of two reciprocal contingency schedules (Allison, 1971). The schedule represented by the steeper line requires that the animal perform one unit of Behavior *x* for each chance to perform Behavior *y*, and then (reciprocally) four units of Behavior *y* for renewed access to *x*. The animal may "climb" the line of constraint at will, up to a limit determined by such variables as the session duration (see Allison, 1983, for further discussion of this kind of representation of schedule constraints).

Suppose the animal were to halt its ascent at the filled circle identified as Point 1. With respect to the paired basepoint at the intersection of the two broken lines, it would appear that the schedule facilitated Behavior *y*—as predicted by various models of performance, such as the linear conservation model (Allison, 1976). But with respect to the baseline function (the line through the five measured basepoints), it appears that the schedule had no effect whatever: The animal merely ascended the line of schedule constraint to its intersection with the baseline function, then stopped. Thus, with respect to the baseline function, the schedule failed to facilitate or "reinforce" Behavior *y*.

But suppose instead that the animal had climbed a bit higher, halting its ascent at Point 3. Relative to the baseline function, Point 3 clearly represents some schedule facilitation of Behavior *y*. To make that conclusion most evident, we have placed Schedule Point 3 directly above a paired-single basepoint, measured by restricting Behavior *x*. In the paired-single test session, the animal could have ascended the vertical constraint line shown in the figure at least as high as Schedule Point 3, but did not do so. Thus, the vertical distance between Point 3 and the baseline function measures a facilitation of Behavior *y* for which the schedule was responsible.

Similarly, Schedule Point 5, below the baseline function, would clearly indicate a schedule suppression of Behavior *y*. Admittedly, no measured basepoint lies directly above Point 5; but the baseline function fits the many measured basepoints so closely that we would readily accept that function as a standard of comparison in lieu of a paired-single basepoint actually measured on a vertical constraint line projected through Point 5.

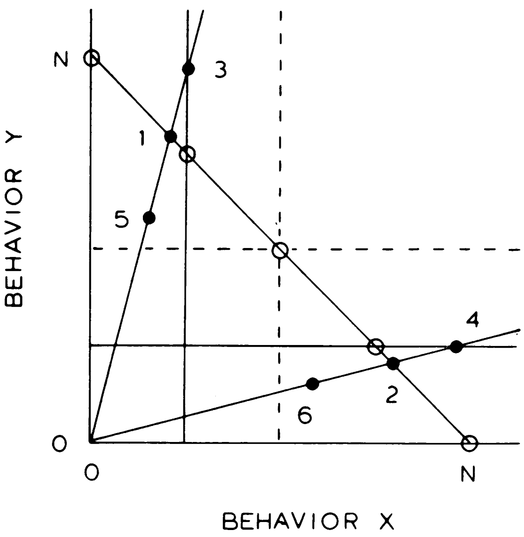

Fig. 3. Illustrative schedule effects in terms of a hypothetical baseline function.

The other schedule in the figure calls for a similar interpretation with respect to the other behavior. Judged in terms of the paired basepoint, Schedule Point 2 would indicate that the schedule facilitated Behavior *x*, a phenomenon predicted by several models (Allison, 1983; Hanson & Timberlake, 1983; Staddon, 1979). But in terms of the baseline function, Point 2 reveals no schedule effect whatever. In contrast, Point 4 (Point 6) lies to the right (left) of the baseline function and therefore indicates a schedule facilitation (suppression) of Behavior *x*, measured by the horizontal distance to the baseline function.

Thus, a baseline function derived from measurements of paired, single, and paired-single basepoints can identify various schedule effects more decisively than any one point on the function. Left of the paired basepoint, this kind of baseline function identifies schedule effects upon Behavior *y*: Only if the schedule function lies above (below) the baseline function did the schedule clearly facilitate (suppress) Behavior *y*. Beneath the paired basepoint, this kind of baseline function identifies schedule effects upon Behavior *x*: Only if the schedule function lies to the right (left) of the baseline function did the schedule clearly facilitate (suppress) Behavior *x*.

EXPERIMENT 1

Experiment 1 studied two highly similar types of behavior, licking water from two identical tubes only a short distance apart. We selected those two in the hope that highly similar types would yield a simple baseline function typical of perfect mutual substitutes. In other words, we hoped that the noncontingent restriction of licks at either tube would result in a linear rise in the number of licks at the other water tube. Schedule effects would be discriminable from noncontingent restriction effects on the basis of a schedule function clearly different from the baseline function.

METHOD

Subjects

We tested three albino rats, experimentally naive males purchased from Laboratory Supply Company (Indianapolis), about 90 days old at the beginning of the experiment.

Apparatus

Testing took place in three identical operant conditioning chambers 26 cm wide, 24 cm deep, and 18.5 cm high, each controlled by a separate microcomputer. Each chamber had a transparent Plexiglas door, and a rear wall made of a black plastic panel; floor, ceiling, and side walls were sheet metal.

Three stainless steel drinking tubes were mounted on the outside of the rear wall. The tip of each tube, 7 cm above the floor, was drilled with a 3-mm aperture. Left, right, and center tubes were 9 cm from the left wall, 9 cm from the right wall, and midway between the others. Thus, the two tubes used in this experiment, left and center, were 4 cm apart. Both contained tap water kept at room temperature.

The tip of each tube lay within easy reach of the rat's tongue through a tapered hole in the plastic wall 1.8 cm wide; the distance between the inside of the wall and the tip was 5 mm. Access to each tube was controlled automatically by an electric motor that raised or lowered a thin metal shutter between the outside of the wall and the tip of the tube. An electronic drinkometer registered each discrete contact between tongue and tube.

In the side wall on the right, 4 cm from the door and 5 cm from the floor, a rectangular cutout 5 cm wide and 2.5 cm high gave continuous access to a food trough filled with powdered laboratory chow. An interior houselight at the center of the chamber ceiling remained dark throughout the experiment; outside illumination came from a 15-W bulb in the ceiling above the chambers. A noise generator masked extraneous sounds.

Procedure

We tamed each rat for several days, during which period the rat had continuous access to free food and water in its home cage. Food remained freely available around the clock during the entire course of the experiment: chow pellets in the home cage, powdered chow in the test chamber. Starting at least 3 days before the rat's first exposure to its test chamber, we confined its home-cage watering to the time reserved for its daily 90-min test session. On the day before its first test session, the rat spent 15 min in the chamber with all tubes closed.

After each test session we recorded the total number of licks directed at each tube, volumetric intake, and total grams of powdered chow eaten from the food trough. In both phases, baseline and schedule, the rat could drink only during the 90-min test session and for 15 min in the home cage immediately after the test session. This supplemental access to free water in the home cage was provided by two stainless steel tubes, identical to those in the test chamber, side by side in the front wall of the cage.

First we presented the center tube alone in a series of test sessions under the single baseline condition, then switched to the left tube alone for another series of single baseline sessions.

Next came a paired baseline series, with both tubes freely available throughout each session.

The baseline phase ended with two series of paired-single sessions. We began each of those sessions by presenting both tubes; we withdrew access to the designated tube after a prescribed number of licks, but the other remained freely accessible for the duration of the session. The first paired-single series restricted licks at the center tube; specifically, we allowed the rat only half the center-tube licks that occurred at its paired basepoint. In the second series of paired-single sessions we restricted licks at the left tube, allowing only half the number that occurred at the paired basepoint.

Each baseline series comprised at least six sessions; we took the individual's mean of the last four sessions as the measure of that particular basepoint. Those last four sessions showed no monotonic change with respect to the total number of licks directed at either tube, and relatively little scatter about the mean; their standard deviation was about 14% of the center-tube mean, and 14% of the left-tube mean.

Immediately after the baseline phase, we measured the schedule functions by testing the rats with five reciprocal fixed-ratio schedules. Each session started with the presentation of the left tube. Upon each completion of the required number of licks, the shutters simultaneously closed the left and opened the center water tube. Upon each completion of the required number of licks at the center tube, the shutters simultaneously closed the center and opened the left tube.

The 4/32 schedule required 4 licks at the left tube for each access to the center, and 32 licks at the center for renewed access to the left. The four remaining schedules required 16/32, 32/32, 64/32, and 256/32 (left-tube licks/center-tube licks).

Each rat was started with the schedule that required the smallest number of licks at the left tube, ascended to progressively higher requirements, and then was exposed to the same schedules in descending order. We tested each schedule in three consecutive sessions in the ascending phase, and three in the descending phase.

We saw no consistent difference between the last two ascending and the last two descending sessions of any schedule. This four-session schedule set showed no monotonic change and little scatter about the mean; for example, the standard deviation of the left-tube totals was only about 4% of the mean. Hence, from each schedule's set of six test sessions we combined the last two from the ascending phase with the last two from the descending phase, and took the four-session mean as the measure of that particular point on the schedule function.

RESULTS AND DISCUSSION

The baseline function showed left and center water licks to be mutual substitutes. That is, the number of licks at the center water tube generally increased as we restricted licks at the left water tube, and conversely. Because the baseline function appeared to be linear, left and center water licks appeared to function as perfect substitutes. The same relation emerged under the constraints of the contingency schedules: Schedule and baseline functions were virtually indistinguishable, both showing the linearity that characterizes perfect substitutes. The functions revealed no significant schedule effect upon either of the two responses.

The evidence for these conclusions appears in Figure 4, which plots by group and by individual rats the number of licks at the center water tube against licks at the left water tube. Unfilled symbols represent basepoints; filled symbols represent schedule points. To avoid clutter, we omit lines of baseline and schedule constraint. Because group data were highly representative of individual data, our narrative will focus on the group.

The top left panel shows the group means ($n = 3$). The paired basepoint, where the broken lines intersect, shows that when both tubes were present the rats directed a substantial number of licks at both. Individual data revealed no reliable group bias toward either tube.

On the left of the paired basepoint appear two additional points that show the typical response to our restriction of licks at the left water tube. The single basepoint for center licks, measured with the left tube absent and

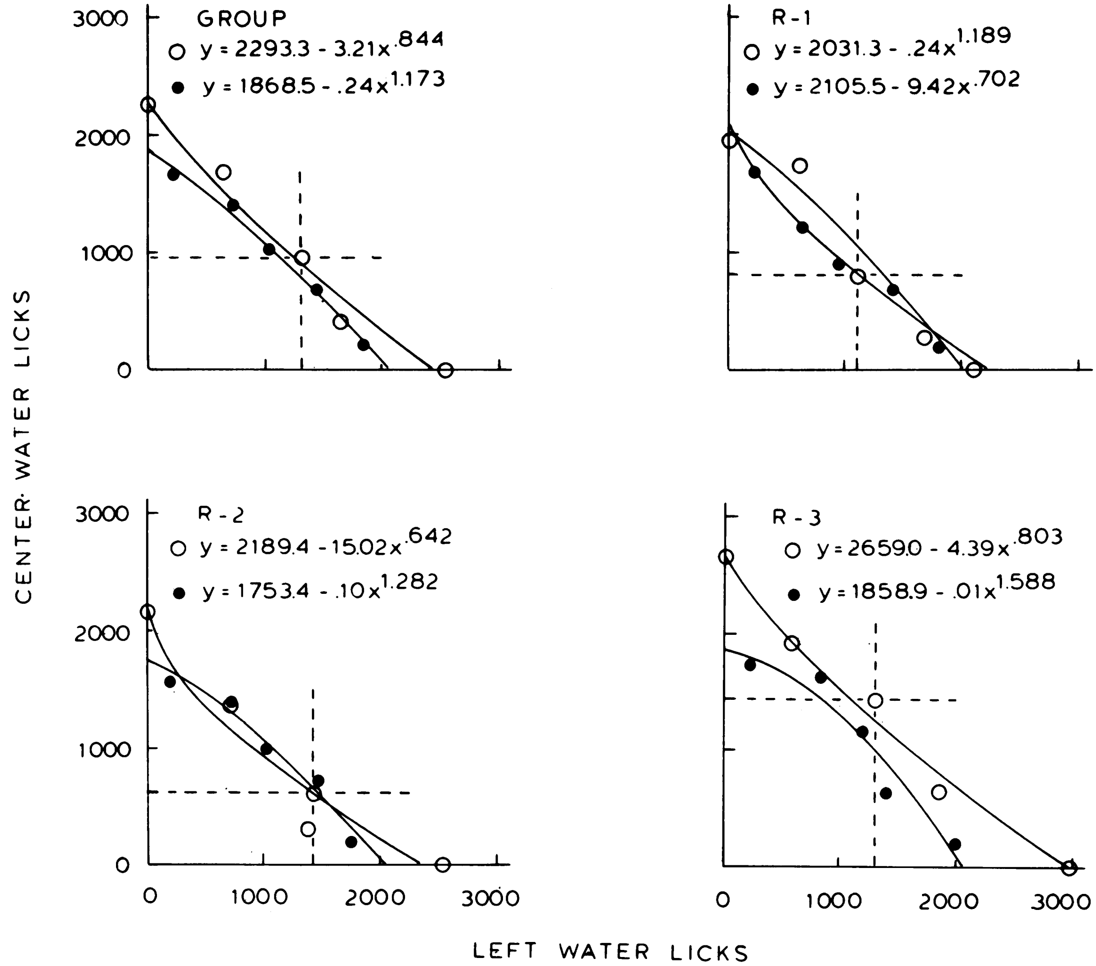

Fig. 4. Licks at the center water tube as a function of licks at the left water tube, under baseline conditions (unfilled circles) and schedule conditions (filled circles).

the center tube present throughout, appears at the extreme left on the vertical axis. About halfway between that and the paired appears a paired-single basepoint, measured by withdrawing the left tube immediately after a prescribed number of licks at it, with the center tube present throughout. Comparison of the three leftmost points shows that the number of licks at the center water tube increased in response to our restriction of licks at the left, and increased directly with the amount of the restriction.

Below the paired basepoint, two additional points show the typical effect of restricting licks at the other (center) tube. The single basepoint for left licks, measured with the center tube absent and the left tube present throughout, appears on the horizontal axis. A paired-single basepoint, about halfway between the horizontal axis and the paired basepoint, was measured by withdrawing the center tube after a prescribed number of center licks, with the left tube present throughout. Those three lowest points show that the number of licks at the left tube increased as we restricted licks at the center, and rose directly with the amount of the restriction.

We inferred the shape of each function by fitting the measured points to a power function, $y = b + kx^n$, where y refers to total licks at the center tube (plotted throughout on the vertical axis); x refers to total licks at the left tube (plotted throughout on the horizontal axis). We calculated least-squares numerical values of the constants b, k, and m iteratively by means of a program that ran on our laboratory microcomputers.

We had no absolutely compelling reason to choose the power function over some other form, but we were influenced by its convenience, its simplicity, its role in psychophysics (Stevens, 1975), and the ease with which it could be mapped into a conservation model of instrumental performance (Allison, 1976). For example, substitutes would generate a negative value for k, so that $y = b - kx^m$: As Behavior x increased, Behavior y decreased. Complements would generate a positive value for k. Perfect substitutes would generate a linear relation—a value of $m = 1$, so that $y = b - kx$: Behavior y decreased linearly as Behavior x increased—a relation predicted by the linear conservation model of instrumental performance (Allison, 1976). Imperfect substitutes would generate a nonlinear function—perhaps concave from the origin ($m > 1$) or, more likely, convex ($0 < m < 1$).

Applied to the group data in Figure 4, our least-squares procedure revealed a baseline function shown as the line fitted to the unfilled basepoints. Numerical values of the three constants also appear in the figure. The fitted baseline function appears very nearly straight to the naked eye; the numerical value of m, 0.844, creates a slight convex bend, but the bend is insignificant statistically.

The claim of no significant bend rests on an analysis of the individual constants shown in Figure 4. Statistical analysis of the three values of m calculated for the individual rats showed that the mean did not differ significantly from 1, $t(2) = 0.75$, $p > .5$. Thus, as licks at the left water tube increased, licks at the center water tube decreased linearly, in the manner of perfect substitutes.

The close approximation to linearity allowed us to fit the group basepoints in Figure 4 with a simple linear regression equation, $y = 2206.3 - 0.94x$, $r^2 = .97$. Because the slope of this linear function, -0.94, is so close to -1, the analysis confirms the visual impression from Figure 4 that the rats in baseline always stood ready to trade about one lick at either tube for one lick at the other. Statistical analysis of individual regression constants supported this conclusion.

The *schedule* function for the group data, the line fitted to the filled symbols, also looks very nearly straight. The numerical value of m, 1.173, creates a concave bend both slight and insignificant; the mean value of m from the individual rats did not differ significantly from 1, $t(2) = 0.73$, $p > .5$. Thus, the rats responded to the schedule constraints in the manner prescribed by the linear conservation model of instrumental performance: As licks at the left water tube increased, licks at the center decreased linearly, in the manner of perfect substitutes. Simple linear-regression analysis of the group schedule points confirmed the impression that the rats always stood ready to trade about one lick at the center water tube for one lick at the left, $y = 1961.1 - 0.91x$, $r^2 = .98$.

With respect to the paired basepoint, the schedules generally produced the pattern of facilitation and suppression effects predicted by conservation and other models related to the response-deprivation hypothesis (Allison, 1983). For example, the conservation model predicts a schedule function that slopes downward through the paired basepoint. Thus, if the schedule's line of constraint passes beneath the paired basepoint, the schedule should facilitate Behavior x and suppress y. Performance under the constraints of all such schedules should therefore lie southeast of the paired basepoint. But a reciprocal schedule whose line of constraint passes above the paired basepoint should produce the reverse pattern, facilitating Behavior y and suppressing x. Performance under the constraints of all such schedules should therefore lie northwest of the paired basepoint. Inspection of Figure 4 shows that the individual rats generally conformed to the predicted pattern, with only 2 exceptions out of 15 opportunities.

But the picture changes dramatically when we step back from the paired basepoint and look at the larger baseline function. With respect to the baseline function, contingency training under the constraints of our five schedules produced no facilitation and no suppression of either behavior. That is, we saw no significant difference between the group baseline and schedule functions shown in Figure 4. Our conclusion rests on statistical analysis of the individual values of the constants b, k, and m in our fitted power function. The analysis revealed no significant difference between baseline and schedule values of any of the three constants. For the intercept constant b, $t(2) = 1.53$, $p > .2$; for the constant k, $t(2) = 0.48$, $p > .6$; and for the exponent m, $t(2) = 0.78$, $p > .5$.

Thus, two highly similar types of behavior began and ended as perfect mutual substitutes, seemingly unaffected by the constraints of the contingency schedules. And the multipoint baseline function made it evident that the schedules produced no contingency effects that differed appreciably from the noncontingent restriction effects of our baseline measurement procedure.

The results led us to speculate that a contingency schedule may have relatively little effect if the two types of behavior controlled by the schedule are intrinsically perfect substitutes. We explored this possibility by reducing the similarity of the two types of behavior, changing the contents of the left tube from water to saccharin.

EXPERIMENT 2

In Experiment 1, we were not particularly surprised to find an inverse linear baseline relation between left and center water licks. Indeed, we choose that pair precisely because its two members seemed so similar as to almost guarantee an experimental example of intrinsically perfect substitutes. The two tubes had identical contents; they differed in location, left and center, but were as near each other as we could get them (only 4 cm apart), given the mechanical constraints of our apparatus.

Each member of our next pair also offered something to drink. But the difference in taste between saccharin and water suggested that their baseline function might show them to be imperfect substitutes rather than perfect substitutes.

METHOD

Subjects

We tested six naive albino rats, 90-day-old males purchased from Laboratory Supply Company.

Apparatus

Except for the contents of the left tube, the apparatus remained unchanged from Experiment 1. We kept both test fluids at room temperature: in the center tube, tap water; in the left tube, a solution of tap water and sodium saccharin, 0.1% by weight.

Procedure

Except as noted below we followed the same procedure used in Experiment 1. After each test session, these rats received in the home cage 15-min free access to two tubes identical to those in the test chamber—saccharin in the left tube, water in the right.

In the order listed, we measured seven basepoints: single water, single saccharin, paired, and four paired-single basepoints. Each of the four paired-single conditions restricted licks at the saccharin tube with respect to its single basepoint: In the order listed, we allowed the rat only half, one fourth, one eighth, and three fourths of the saccharin licks that occurred at the single basepoint for saccharin.

We tested these animals with seven schedules. The 4/32 schedule required 4 licks at the left saccharin tube for each access to water, and 32 licks at the center water tube for renewed access to saccharin. The six remaining schedules required 8/32, 16/32, 32/32, 64/32, 128/32, and 256/32.

The four sessions whose mean defined any particular basepoint showed no monotonic change and little dispersion; their standard deviation was about 15% of the water-tube mean and 4% of the saccharin-tube mean. The four sessions whose mean defined any particular point on the schedule function showed no consistent difference between the ascending and the descending phase, no monotonic change, and very little scatter; for example, the standard deviation of the saccharin-tube totals was only about 1% of the mean.

RESULTS AND DISCUSSION

Group means ($n = 6$) appear in the top left panel of Figure 5, with licks at the water tube

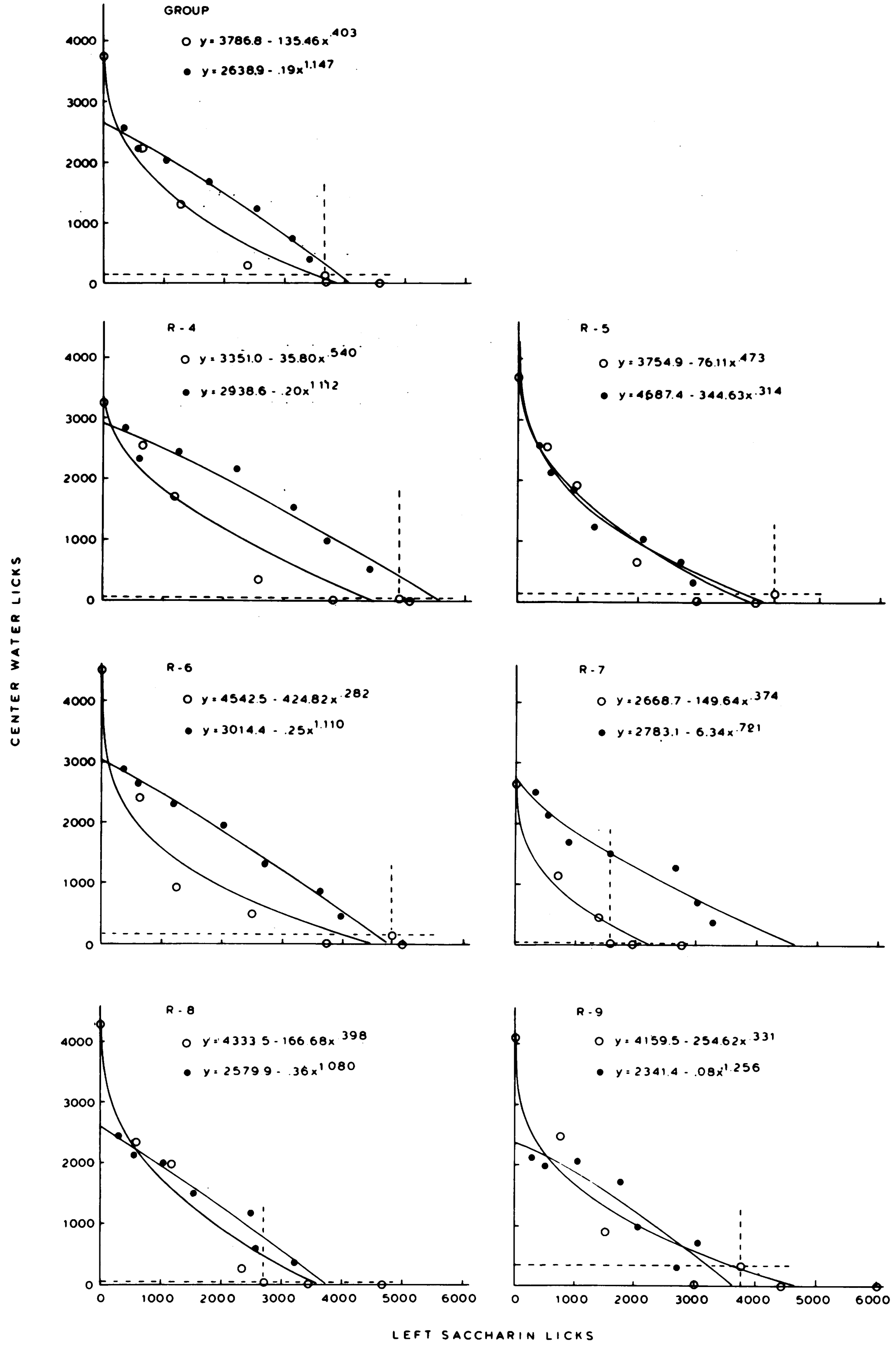

Fig. 5. Licks at the center water tube as a function of licks at the left saccharin tube, under baseline conditions (unfilled circles) and schedule conditions (filled circles).

plotted against licks at the saccharin tube. The individual paired basepoints show that when both tubes were present, each of the six rats directed some licks at the water tube, but a great many more at the saccharin. The single basepoints reveal an equally consistent difference in favor of the saccharin tube, but a much smaller one.

The baseline data showed water licks and saccharin licks to be imperfect substitutes. The power function fitted to the group basepoints follows a definite convex bend ($m = 0.403$) that was characteristic of all six rats. The individual values of the exponent m ranged from 0.282 to 0.540, and their mean differed significantly from 1, $t(5) = 15.62$, $p < .001$. For every rat, as licks at the saccharin tube increased, licks at the water tube fell steeply and then more gradually, in the manner of imperfect substitutes.

But training under schedule constraint seems to have converted those intrinsically imperfect substitutes into perfect ones. The power function fitted to the group schedule points looks almost straight. The fitted value of m, 1.147, creates a slight concave bend, but the bend was not significant statistically; the mean value of m from the individual rats did not differ significantly from 1, $t(5) = 0.47$, $p > .6$. Like the rats tested with the water-water pair, these rats responded under the schedule constraints in the manner predicted by the linear conservation model: As licks at the saccharin tube increased, licks at the water tube decreased linearly.

Under those schedule constraints, the rats generally traded about 0.65 licks at the water tube for one lick at the saccharin: Applied to the group schedule points, simple linear regression yielded $y = 2740.2 - 0.65x$, $r^2 = .98$. Individual slope constants ranged from -0.77 to -0.52, r^2s from .84 to .99. And the linear schedule function for the group data passes very near the paired basepoint, in agreement with the conservation model, although some of the individual functions do not pass so near their paired basepoints.

With respect to the baseline function, the schedule function was generally higher throughout the midrange, but not at either extreme. Thus, the intermediate schedules generally facilitated water licking, while schedules at either extreme had little or no effect.

The pattern formed by Experiments 1 and 2 suggests that the behavioral effects of a contingency schedule may depend on the intrinsic substitutability of the two types of behavior controlled by the schedule. In the first experiment two highly similar types, left and center water licks, began as perfect substitutes and showed no apparent change under schedule constraint. The second experiment dealt with two less similar types, saccharin licks and water licks. These began as imperfect substitutes and showed an unmistakable sensitivity to schedule constraint: Intermediate schedules facilitated the licking of water, and the two types functioned as perfect substitutes under schedule constraint. Experiment 3 sought to test and extend this pattern by reducing the similarity still further. Specifically, Experiment 3 paired the center water tube used in the first two experiments with a dry metal tube on the left.

EXPERIMENT 3

We presume that the intrinsic substitutability of two different types of behavior depends in part on features they have in common. Thus, left and center water licks shared many intrinsic features, and functioned in baseline as perfect substitutes. Left saccharin and center water licks shared fewer features, and functioned in baseline as only imperfect substitutes.

Operant conditioning experiments often use behavioral pairs whose members seem to share very few intrinsic features. For example, pressing a lever and eating may seem so unrelated that we might expect them to function as intrinsic independents. The members of our third and final pair had the same general topography as the others, but shared even fewer features than the saccharin-water pair: The rat could still lick either tube, but while the center tube contained water as usual, the left tube was empty. Thus, we were prepared to see less intrinsic substitutability with our dry-water pair than we saw with the water-water or the saccharin-water pair.

METHOD

Subjects

We tested five naive albino rats, 90-day-old males from Laboratory Supply Company.

Apparatus

As in the first two experiments, the center tube was filled with tap water kept at room temperature. The left tube was empty.

Procedure

Except as noted, we followed the same general procedure used in the first two experiments. We measured seven basepoints in the order listed: single basepoints for the water tube and the dry tube, the paired basepoint, and four paired-single basepoints. Each of those four was measured by restricting licks at the water tube. Specifically, the first, second, and fourth allowed only one half, one fourth, and one eighth of the water licks that occurred at the single basepoint for water. We measured the third by limiting water licks to a value halfway between the paired basepoint and the first paired-single basepoint.

The rats were tested with eight schedules. The 2/192 schedule required 2 licks at the left dry tube for each access to water, and 192 licks at the center water tube for the next access to the dry tube. The next five schedules required 4/192, 8/192, 16/192, 32/192, and 64/192. The next schedule doubled the dry-lick requirement and halved the water-lick requirement, 128/96. The eighth schedule maintained the last dry-lick requirement and quartered the water, 128/24.

Except as noted below, these rats received in the home cage after each test session 15-min free access to two tubes identical to those used in the test chamber—a dry tube on the left, water on the right. To ensure adequate daily access to water, we decided in advance to extend that free access to 30 min during the following measurements: the single dry-lick basepoint, and paired-single basepoints that limited the rat to less than half of its single water-lick basepoint.

Three of these rats had single dry-lick basepoints that were so surprisingly high that we decided to measure them again at the very end of the baseline phase. But, as we found no large or consistent difference between the first and second measurements, we took their mean as the measure of the single dry-lick basepoint.

The four sessions whose mean defined any particular basepoint showed no monotonic change and little scatter; their standard deviation was about 4% of the water-tube mean and 30% of the much smaller dry-tube mean. The four sessions whose mean defined any particular point on the schedule function showed no consistent difference between the ascending and the descending phase, no monotonic change, and very little scatter.

RESULTS AND DISCUSSION

The baseline data showed dry and water licks to be imperfect mutual substitutes—more like the saccharin-water than the water-water pair, but decidedly different from either of those pairs. These data appear in Figure 6, which plots licks at the water tube against licks at the dry tube.

The paired basepoints reveal some licks at both tubes when both were present, but many more licks at the water tube than at the dry tube. The single basepoints on the vertical axes show that when the dry tube was absent, water licks rose above the paired basepoint in four of the five rats, $t(4) = 3.09$, $p < .05$. Single basepoints on the horizontal axes show that when the water tube was absent, all five rats exceeded the dry paired basepoint. But the restriction of licks at the center water tube generally resulted in a much smaller substitution rise in licks at the left dry tube than at the water tube in Experiment 1 or the saccharin tube in Experiment 2.

Thus, the group means ($n = 5$) reveal a relatively steep baseline function; and the function is definitely convex as viewed from the origin ($m = 0.351$), in a manner characteristic of imperfect substitutes. Individual baseline values of m ranged from 0.238 to 0.577; their mean differed significantly from 1, $t(4) = 11.09$, $p < .001$.

In contrast, the power function fitted to the group schedule points looks very nearly linear ($m = 0.942$). This apparent linearity suggests

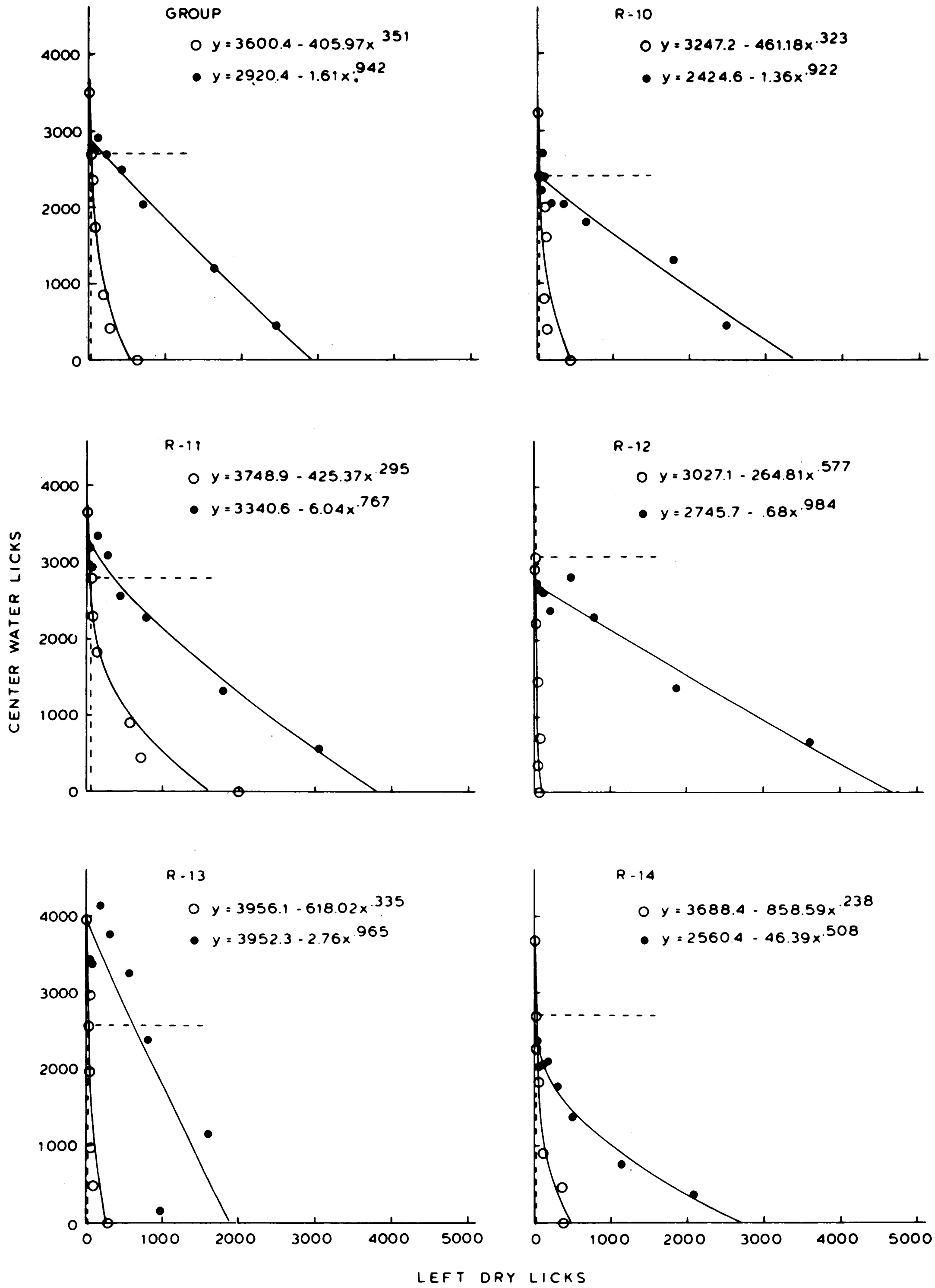

Fig. 6. Licks at the center water tube as a function of licks at the left dry tube, under baseline conditions (unfilled circles) and schedule conditions (filled circles).

that training under schedule constraint converted those intrinsically imperfect substitutes into perfect substitutes, as it did with the saccharin-water pair.

Closer analysis of schedule functions confirmed the impression of linearity. Although the individual values of m ranged from 0.508 to a high of only 0.984, their mean did not differ significantly from 1, $t(4) = 1.92$, $p > .1$. And each of the five rats displayed a greater value of m in its schedule function than in its baseline function, $t(4) = 7.25$, $p < .01$.

Under schedule constraint, the rats generally traded about one lick at the water tube for one lick at the dry: Applied to the group schedule points, simple linear-regression analysis yielded $y = 2890.1 - 1.02x$, $r^2 = .99$. Individual slope constants ranged from -2.13 to -0.60, r^2s from .67 to .96. Thus, licks at the water tube decreased linearly as licks at the dry tube increased, in accordance with the linear conservation model of performance under schedule constraint. In accordance with that model, the schedule function for the group data in Figure 6 passes near the paired basepoint, although some of the individual functions do not pass so near theirs.

The schedule function sloped far to the right of the baseline function from the midrange on down: Their horizontal displacement, minimal at the upper extreme, increased systematically from there on down. Thus, with respect to the baseline function, most of the schedules facilitated licking of the dry tube, and the magnitude of the facilitation effect increased systematically as the dry/water ratio enforced by the schedule increased.

GROUP COMPARISONS

To aid comparison of the three behavioral pairs, we collect in the left panel of Figure 7 the group basepoints and the three fitted power functions. The middle function (squares) refers to the water-water pair, essentially a linear baseline function with a slope near -1: perfect substitutes, virtually interchangeable, each highly and uniformly responsive to restrictions in the other. In distinct contrast are the other two functions, saccharin-water (triangles) and dry-water (circles). Each is convex to the origin, suggestive of imperfect substitutes whose marginal rate of substitution, far from constant, changes systematically as we move along each curve.

To help compare the effects of schedule constraint, we collect in the right panel of Figure 7 the group schedule points and their fitted power functions. As noted above, all three schedule functions were essentially linear.

Thus, under schedule constraint left and center water licks (squares) remained perfect substitutes and retained their original rate of exchange, about one to one. Dry licks and water licks (circles) became perfect substitutes and assumed a rate of exchange, about one to one, that did not differ appreciably from that of the water-water pair. Saccharin licks and water licks (triangles) also became perfect substitutes, but they assumed a rate of exchange considerably different from that of any other pair—about 0.65 water licks to one saccharin lick.

Those similarities and differences in the linear slope constants, readily apparent in the right panel of Figure 7, were confirmed by statistical tests. The tests revealed no significant difference in slope between the water-water group and the dry-water group, but a highly reliable difference between those two groups combined and the saccharin-water group, $U(8, 6) = 5$, $p = .012$ (heterogeneous variances indicated a nonparametric test). Each of the three rats in the water-water group also had a lower linear intercept than any of the other 11 rats, perhaps reflecting a sampling difference in baseline fluid intake.

GENERAL DISCUSSION

As one might have predicted from an advance comparison of features held in common, our baseline functions revealed left and center water licks as intrinsically perfect substitutes, but the members of the other two pairs, saccharin-water and dry-water, as imperfect substitutes. In agreement with the linear conservation model (Allison, 1976), our schedule functions showed the members of each pair to be perfect substitutes. We saw no extrinsic

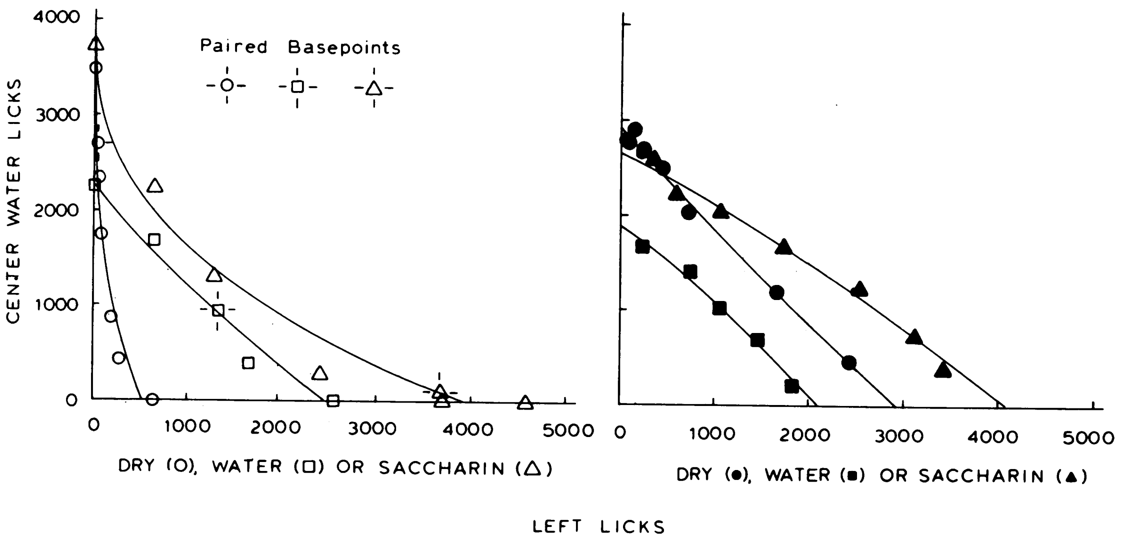

Fig. 7. Licks at the center water tube as a function of licks at the left water, saccharin, or dry tube, under baseline conditions (left panel) and schedule conditions (right panel); group data.

schedule effects on the water-water pair, but large effects upon the others, especially the dry-water pair. The baseline functions generally provided a more adequate standard for the evaluation of schedule effects than did any particular basepoint. Those functions revealed clear schedule facilitation of water licks in the saccharin-water pair, and of dry licks in the dry-water pair.

There are other ways of measuring noncontingent restriction effects, and they might serve certain purposes better than the procedure used here. To illustrate one important alternative, we refer again to Figure 1. Suppose we wish to see how many licks the rat will direct at Tube *y*, given that the rat has made exactly 5*a* licks at Tube *x*. To get that information, we cannot depend on the paired-single procedure. The reason is simple. If we start the session by presenting both tubes, as we must by definition of the paired-single condition, it will probably be fruitless to wait for as many as 5*a* licks at Tube *x*; the rat will probably end the session at its paired basepoint, 2*a* licks at Tube *y* and only 4*a* licks at Tube *x*—short of our prescribed number, 5*a*. The session will therefore end with both tubes still available, and the "paired-single" session will have been in fact only a paired baseline session.

But a glance at the single basepoint suggests an effective alternative to the paired-single procedure. The single basepoint, 6*a* licks at Tube *x*, shows that if we present Tube *x* alone, the rat will surely surpass its paired basepoint (4*a*) and go on to perform our prescribed number of licks (5*a*). These considerations suggest the use of a *single-single* session that starts with the presentation of Tube *x* alone, just as in a conventional single baseline session; but when the rat completes 5*a* licks, we withdraw Tube *x* and present Tube *y* alone, leaving it there for the rest of the session.

With the help of another earlier figure, Figure 3, one can readily see the potential use of measurements made under the single-single condition. Thanks to the baseline function displayed in Figure 3, Schedule Point 6 clearly represents a schedule suppression of Behavior *x*: Point 6 lies to the left of the baseline function. But what schedule effect, if any, does the same point represent with respect to the other behavior, Behavior *y*? To answer that question more directly, we need an experimental procedure that can provide a vertical line of noncontingent constraint that projects through Schedule Point 6. Given the paired and single basepoints shown in Figure 3, this is a line that we probably cannot realize under the paired-single condition, but that we can certainly realize under the single-single condition. The rest is straightforward: If Schedule Point 6 turns out to lie above (below) the single-single basepoint measured on the vertical line of constraint projected through Point 6, then the schedule probably facilitated (suppressed) Behavior *y*.

Now we can state in more general terms the roles of these baseline-measurement procedures in the evaluation of schedule effects. With respect to Behavior *x* (*y*), we may evaluate schedule effects in terms of basepoints measured along horizontal (vertical) lines of noncontingent constraint. If our own three pairs are any indication, the single basepoint of each behavior will often exceed its paired basepoint, as in Figure 3. In that event, the following statements will generally apply. In the space beneath the paired basepoint, horizontal lines of noncontingent constraint can be provided by both procedures, paired-single and single-single. Above the paired basepoint, the single-single procedure can provide horizontal lines of noncontingent constraint, but the paired-single cannot. In the space to the left of the paired basepoint, vertical lines of noncontingent constraint can be provided by both procedures; to the right the single-single procedure can provide such lines, but the paired-single cannot.

If the single-single procedure can cover more ground, why bother with the paired-single procedure? We feel that a careful comparison of the two procedures must concede a major point to the paired-single. To appreciate this point, one must recognize that the two procedures may give different results. Notice that the single-single procedure will force upon the animal's behavior an organizational pattern that the paired-single will not. Specifically, in a single-single session the animal cannot alternate freely between the two activities; only when it has completed the prescribed amount of the first activity can it turn to the other. In contrast, the paired-single condition has an initial paired segment that allows unrestricted alternation. Thus, even when the two conditions prescribe and produce exactly the same total amount of the restricted behavior, the behavioral pattern enforced by the single-single condition may differ from the one typically followed under the paired-single condition. And the pattern itself, or the mere enforcement of a pattern, may influence the animal's subsequent behavior in the absence of external constraint. It follows that the single-single basepoint may differ from the paired-single basepoint, even though both basepoints lie on the same line of noncontingent constraint; and any such difference might proceed from the structural difference between the two baseline procedures.

We therefore advocate caution in the use of the single-single condition as a basis for evaluating schedule effects. Operationally, it appears less free of schedule-like constraints than the paired, the single, or the paired-single condition: In any single-single baseline session, the chance to engage in one type of behavior is contingent on performance of the other.

So far, we have offered no explanation of our schedules' transformation of imperfect substitutes into perfect ones. The data undoubtedly permit many alternative interpretations, perhaps even some that would assign no major role to learning. But we would like to offer a speculative account in which learning does play a prominent part—as we think it would in any satisfactory account of a human who did not as an infant, but who does now as an adult, treat nickels and dimes as perfect substitutes.

Under the conditions of our baseline procedure, neither member of the behavioral pair has functioned as a means of gaining access to the other. But the conditions of a reciprocal contingency schedule give that very status to both members: Each of the two types of behavior is now the necessary and sufficient means of engaging in more of the other. On the basis of that functional similarity, they become or remain perfect substitutes. Thus, by the present account our reciprocal contingency schedules taught our rats to treat intrinsically imperfect substitutes as perfect ones: the members of the saccharin-water pair and the dry-water pair. Because left and center water licks were already perfect substitutes, our schedules wrought no extrinsic change in the intrinsic relation between those two types of behavior.

To complete our account, we must answer

one final question: How high will the animal ascend the line of schedule constraint? The answer must come from some model of instrumental performance. The linear conservation model that fits our three schedule functions answers this question by appealing to some unspecified dimension whose total amount the animal conserves, or holds constant, among all of the schedules under test. Once it achieves that constant total, b, the animal ascends no further. Suppose one unit of Behavior y contributes one unit of the dimension conserved, and one unit of Behavior x contributes k units of the same dimension. Then the two behavioral totals, x and y, on any particular schedule, will satisfy the following constraint: $b = y + kx$, from which $y = b - kx$. This theoretical constraint generates a schedule performance function like each of our three functions, in which the total amount of Behavior y falls linearly as total Behavior x rises. And, because the same theoretical constraint—$b = y + kx$—supposedly applies to the paired basepoint, the linear schedule function should slope downward through the paired basepoint. The model does not predict the numerical value of the slope constant k. But the numerical value of k presumably depends on the identity of the dimension conserved.

We were surprised to see the linear conservation model fare as well as it did. We were equally surprised to see several other models, relatively intolerant of linearity (Hanson & Timberlake, 1983; Rachlin & Burkhard, 1978; Staddon, 1979), fare so poorly. The reason for our surprise is that we expected to find a concave schedule function with the dry-water pair, not the linear function actually found. When rats press levers instrumentally, with contingent access to such goods as food, water, or sugar water, the schedule function often falls linearly throughout the upper and middle part of the bivariate space. But it often takes a concave bend at the highest fixed-ratio requirements, sometimes bending back on itself (Allison, 1983). We can readily understand how intrinsically perfect substitutes, like left and center water licks, might generate a linear schedule function. But at present we can only speculate about the possible reasons for the lack of a backward bend in our schedule function for the dry-water pair.

We think the answer will probably not be found in the distinction between open and closed economies. According to Hursh (1980), the open economy is an experimental arrangement in which daily consumption can vary independently of consumption during the daily test session, while in the closed economy, all consumption must occur within the daily test session. Hursh proposes that monotonic schedule functions like ours, which signify an inelastic demand for water (Allison, 1979, 1983; Allison et al., 1979; Hursh, 1980), are most likely to occur in a closed economy, where the animal receives no free supplement to the rations it earns during the daily test session. A backward-bending schedule function, signifying elastic demand for water, is most likely to occur in an open economy, where the animal receives a free supplement to the water earned during the daily test session. Thus, one might explain our linear schedule functions as the characteristic result of a closed economy.

We reject that interpretation, because we think our economy was more open than closed. Whatever the amount drunk during the daily test session, the rat always had the chance to drink a large additional amount just a few minutes later. Right after each test session, back in its home cage, each rat had at least 15 min of free access to two tubes identical to those under test, one always a water tube. At approximately 5 licks/s (Allison & Castellan, 1970), those 15 min in the home cage would allow approximately 4500 water licks—comparable to the largest number observed in our 90-min baseline and schedule sessions (see Figure 7).

If our economy was more open than closed, we can hardly explain our linear schedule functions, signifying inelastic demand for water, as the characteristic result of a closed economy. Perhaps rats are simply not very sensitive to rations consumed freely soon after sessions in which they have responded instrumentally for similar goods (Timberlake, 1984). For another critique of the open-closed distinction, see Allison (1983).

Other possibilities seem more promising.

We note the topographical similarity between dry licks and water licks. We note too that it may typically cost less energy to lick a tube instrumentally than it does to press a lever. But we find most noteworthy another distinctive feature of our dry-water schedules that is not peculiar to licking or, indeed, to any particular behavior.

Recall that we formed six of our eight fixed-ratio schedules by a progressive doubling of the instrumental dry-lick requirement, holding the number of contingent water licks constant at 192: 2/192, 4/192, 8/192, 16/192, 32/192, and 64/192. We formed the seventh schedule by making two changes that we thought would finally produce some semblance of a bend in the schedule function: We again doubled the instrumental dry-lick requirement, and halved the number of contingent water licks, to 128/96. Still we saw no bend.

In forming our eighth schedule, we wished to define a line of schedule constraint with a still gentler slope than the others, but without imposing an even larger instrumental requirement. Accordingly, we made no change in the instrumental requirement, but quartered the number of contingent water licks: 128/24. But again we saw no significant bend in the schedule function.

Perhaps we would have seen a backward bend if we had formed our schedules in the conventional way, raising the instrumental (fixed-ratio) requirement to even higher values while holding constant the magnitude of the contingent reward. By the same logic, perhaps we can generally remove or moderate the bend simply by selecting more tolerable values for the *two* variables that actually specify all ratio schedules: the size of the instrumental requirement and the magnitude of the contingent reward. Thus, even though all three lines of schedule constraint have the same slope, the animal may climb further up a 100/10 line than either a 1000/100 line or a 10/1 line. The second instrumental requirement (1000) may somehow be too large, and the third contingent reward (1) too small.

Linear schedule functions have many attractive features. We note in particular a potential ability to predict very simply, but in unusual detail, the effects of schedules imposed on a novel pair (Allison et al., 1979). By "novel pair" we mean two types of behavior that have already been tested in combination with other types, but never in combination with each other. Thus, having measured the slopes of the schedule functions for the saccharin-water pair and the dry-water pair in Experiments 2 and 3, we can predict the slope of the schedule function for a novel pair, the dry-saccharin combination. The same feature may let us predict from general principles (Allison et al., 1979) a peculiar pattern of constraints on behavior (e.g., Shettleworth, 1975) that has led many investigators to suspect a need for special principles. For example, if the predicted slope of the schedule function is extremely steep (flat), then we would expect Behavior x (y) to prove highly resistant to the influence of schedules.

For a time we feared that a prevalence of nonlinear functions would preclude any widespread use of this simple predictive potential. But our present results, which yielded nothing but linear schedule functions, suggest that the field of application may be larger than we had anticipated.

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