THE EFFECTS OF CONCURRENT RESPONDING AND REINFORCEMENT ON BEHAVIORAL OUTPUT

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Four birds key pecked on concurrent variable-interval one-minute variable-interval four-minute schedules with a two-second changeover delay. Response rates to the variable-interval one-minute key were then reduced by signaling its reinforcer availability and later by providing its reinforcers independently of responding. Each manipulation increased response rates to the variable-interval four-minute key even though relative reinforcement rates were unchanged. In a final phase, eliminating the variable-interval one-minute key and its schedule produced the highest rates of all to the variable-interval four-minute key. These results show that both reinforcement and response rates to one schedule influence response rates to another schedule. These results join those of Guilkey, Shull, & Brownstein (1975) in failing to replicate Catania (1963). Moreover, they violate the predictions of the equation for simple action (de Villiers & Herrnstein, 1976). In terms of a median-rate measure (reciprocal of the median interresponse time), rates to the variable-interval four-minute key were high when responding was not reduced to the variable-interval one-minute key and were low when it was reduced. This rate difference suggests a process difference between concurrent-schedule procedures that maintain high concurrent response rates versus those that do not. This process difference jeopardizes attempts to integrate single- and concurrent-operant performances within a single formulation.

Key words: concurrent schedules, equation-for-simple-action, matching law, response independence, key peck, pigeons

Herrnstein's (1970) equation for simple action can be written as

$$R = \frac{kr}{r+r_e} \qquad \text{(Equation 1)}$$

where R and r respectively specify some dimension of behavior and reinforcement, k equals the maximum level of behavioral output, and the presence vs. absence of the subscript e distinguishes experimenter-arranged reinforcement contingencies (r) from those present for "other" behavior (r_e).

Central to the generality of Equation 1 is the notion of "other" or "extraneous" reinforcement. Like concurrent schedules, single schedules also involve a choice—in the case of Equation 1 between some explicit reinforcement schedule arranged by the experimenter and an assumed extraneous schedule provided

naturally by the environment. For example, a pigeon responding on a single variable-interval (VI) schedule of food reinforcement may choose between some explicit reinforcement schedule arranged by the experimenter and an assumed extraneous schedule that reinforces preening, defecating, etc. By viewing this extraneous schedule as providing a certain rate of reinforcement, Herrnstein showed that Equation 1 could predict the rate changes normally found when VI reinforcement frequency is varied (see Catania & Reynolds, 1968).

Equation 1 attributes shifts in response rate (R) to changes in reinforcement (r or r_e), but not to the operants R and R_e that they support. By ignoring these response factors, this equation for simple action makes a testable prediction—that the response rate maintained by a schedule of reinforcement will be affected by the rate of alternative reinforcement but not the rate of alternative responding.

Consistent with this interpretation are the results of a study by Catania (1963). In Experiment 1, he exposed three birds to concurrent VI 3-min VI X schedules where X

provided between 0 and 40 reinforcers/hr across five conditions. One key, the change-over (CO) key, switched the key-color/schedule pair in effect on the other key. Pecks to the CO key began a 2-sec delay (changeover delay or COD) during which reinforcement was unavailable for a peck to the other key. In Experiment 2, he repeated this procedure except that he illuminated the CO key only when reinforcement was available on the VI X schedule. He reported two major findings: First, in both experiments there was an inverse relation between the rate of reinforcement provided by the altered schedule and the response rate maintained by the VI 3-min schedule. Second, although the signaling of reinforcer availability for one alternative in Experiment 2 led to a dramatic increase in time allocated to the unsignaled VI 3-min schedule, the number of pecks to this key per session was essentially unchanged from Experiment 1 for two of the three birds.

Within each experiment of this study, responding was inversely related to the rate of alternative reinforcement, yet the response rate to one key was uninfluenced by the response rate to the other. These results provide important empirical support for Equation 1: Consistent with its definition, response rate seems to be affected by other sources of reinforecment but not by other loci of behavior.

However, subsequent work by Guilkey, Shull, and Brownstein (1975) amends this conclusion. Like Catania, they varied the rate of reinforcement provided by one schedule and recorded the response rate to the unaltered key when reinforcer availability on the altered key was unsignaled (baseline condition) and signaled (signal condition). In both conditions they found an inverse relation between the rate of reinforcement provided by the altered schedule and the response rate to the unaltered key. But for five of six birds, the response rates were consistently higher to the unaltered key when reinforcers were signaled than when they were not. The data from Guilkey et al. violate the equation for simple action because interference occurred between concurrent operants even though this equation assigns no role to an interference factor. Moreover, this incompatibility is not apparent in a parametric fit of Equation 1 to the Guilkey et al. data: The mean percentages of the data variance ac-

counted for by Equation 1 in the baseline and signal conditions are 86.3 and 83.4 respectively (nonlinear least-squares method of Wetherington & Lucas, 1980).

The correspondence between the predictions of Equation 1 and the data from Guilkey et al. is significant because a popular test of Equation 1 has been to show in a variety of single-schedule contexts that it accounts for substantial portions of the data variance (e.g., de Villiers & Herrnstein, 1976: Rachlin & Baum, 1972). That the equation works well in the Guilkey et al. study, where by definition it errs, suggests that cataloguing the portion of data variance Equation 1 accommodates in different studies cannot, by itself, test the adequacy of this equation.

For Equation 1 to describe the process by which behavior is maintained by reinforcement, it must be shown by a response independence test that typically responding to one locus does not interact with responding to another. Interestingly, few studies exist which make this assessment, and those that do suggest that the Guilkey et al. findings are not the exception but the rule (Bradshaw, Szabadi, Bevan, & Ruddle, 1979; Pliskoff & Green, 1972).

Independence between concurrent operants is a requisite for claiming the equation for simple action completely characterizes the process governing behavioral output. We propose to test for independence in a procedure where involvement between concurrent operants can be graded from situations where it is minimal (e.g., Catania's signal condition) to where it is maximal (e.g., his unsignaled condition). Toward this end the present study uses concurrent VI VI schedules where the response requirement to one key is altered by (1) eliminating the COD, (2) signaling reinforcer availability, and (3) presenting its reinforcers on a response-independent basis. In a final manipulation, the changed key is no longer illuminated and its associated schedule is placed in extinction (EXT). The purpose of this condition is to compare the effects of reducing response interaction with the effects of eliminating reinforcer interaction.

METHOD

Subjects

Four adult male White Carneaux pigeons

(B30, B31, B32, B33), maintained at 80% of their free-feeding weights, served. All birds had extensive experience with choice and multiple-schedule procedures.

Apparatus

Four identical chambers, measuring internally 27.5 by 32.5 by 29 cm, individually housed a single subject. With the exception of a stainless steel response panel and a wire mesh floor, all internal surfaces were made of galvanized steel. The distances from the floor to the bottom of the 5.5 by 5 cm hopper aperture and the houselight were 5.5 and 26.2 cm, respectively. Three 2.54-cm diameter Lehigh Valley Electronics response keys, spaced 6.5 cm apart center to center, were located 21 cm above the floor. Each key operated at a minimum force of .15 N. The keys were transilluminated from behind the response panel by Industrial Electronics Engineers multistimulus projectors. A PDP-8/e minicomputer controlled all experimental events and data collection.

Procedure

The procedures can be divided into three major categories—those involving concurrent VI VI schedules, concurrent VI variable time (VT) schedules, and a single VI schedule.

Concurrent VI VI schedules. There were four types of choice procedures in this study: choice with a COD (*Ch+COD*), choice with a COD and signaled reinforcement (*Ch+COD+sig*), choice with signaled reinforcement but no COD (*Ch+sig*), and choice with neither COD nor signaling (*Ch*).

For the *Ch* procedure, responses to the left and right key produced three seconds of access to grain according to VI 1-min and VI 4-min schedules, respectively. Each VI schedule was composed of 20 different interreinforcement intervals generated by the formulation of Fleshler and Hoffman (1962). Each VI timer operated continuously except if the magazine was operated or if it had assigned a reinforcer not yet obtained. For Birds B30 and B31 the right key was red and the left key was green; for Birds B32 and B33, these key colors were reversed. The keylights and houselight were illuminated throughout the session except during hopper presentations. Each session lasted for 50 hopper presentations, and the experimental condition lasted until all response rates

to the VI 4-min key were judged by the experimenter to be stable for five sessions.

The *Ch+COD* procedure differed from the *Ch* procedure in only one way: The reinforcers assigned by either VI schedule were unavailable for the first two seconds following a changeover between keys. These reinforcers were delivered for the first response after two seconds had elapsed since a changeover to that key (COD 2-sec; see Herrnstein, 1961).

The *Ch+COD+sig* procedure duplicated the prior condition except that the VI 1-min key was illuminated only when its associated VI timer had assigned a reinforcer. At that time, the key was illuminated by white and remained so until reinforcement occurred.

In the *Ch+sig* procedure, the only change from the *Ch+COD+sig* condition was the elimination of the COD requirement. In other words, VI 1-min reinforcement was cued by the illumination of its associated key with white light. The changeover to that key produced reinforcement.

Concurrent VI VT schedules. Three types of VI VT schedules were used in this study: one where the key formerly associated with the VI 1-min schedule remained lit while the schedule was changed to a VT 1-min (*VT+lit*); where the key was not lit (*VT*); and where this key was not lit and there was a 2-sec minimum delay between successive hopper presentations (*VT+del*).

The *VT+lit* condition was identical to the *Ch* procedure except that reinforcers arranged by the VI 1-min schedule were delivered immediately upon assignment without any required response. The *VT* procedure was identical to this procedure except that only the key associated with the VI 4-min schedule was illuminated. Finally, in the *VT+del* condition, the *VT* procedure was duplicated except that successive reinforcers were not delivered if they were within two seconds of the prior reinforcement.

Single VI schedule. Called the *SS* (single schedule) procedure, the experimental contingencies in this condition were altered from those in the *VT* procedure in two ways: (1) the VT schedule became EXT; and (2) sessions terminated after 1 hr. In other words, only the VI 4-min schedule and its associated key were available during the 1-hr session.

Table 1 presents all the conditions of the experiment in their order of occurrence (iden-

tified by phase number in the table), and the number of sessions a condition was in effect. In all phases, the VI 4-min schedule remained in effect on the right key. All data analyses were based on the means of the last five sessions of each condition.

Table 1

Order of Conditions and Number of Sessions

Phase Number	Condition	Number of Sessions
1	Ch+COD	17
2	Ch+COD+sig	15
3	VT+del	16
4	Ch+COD	30
5	VT+del	15
6	SS	21
7	VT	36
8	Ch	27
9	VT	27
10	SS	45
11	Ch	30
12	VT+lit	27
13	Ch+sig	18

RESULTS

The unfilled and hatched bars of Figure 1 present the mean rate in responses per min to the VI 4-min and VI 1-min keys respectively for the 13 phases of this experiment. The top four panels present individual data identified by bird numbers within each panel. The bottom panel presents group mean data. Different conditions within each panel are labeled at the top of the figure. Since the three types of VT procedures produced no noteworthy differences in response rate, they are all combined under the heading of VT.

The first five panels of Figure 1 rank order experimental conditions in terms of the amount of responding they maintained to the VI 1-min key. For example, the *Ch+COD* condition and the *Ch* condition supported the two highest VI 1-min rates, in that order. Hence, they occupy the first and second panels of the figure. In scanning the first five panels from left to right we see that as rates to the VI 1-min key decreased, rates to the unchanged VI 4-min key increased. This result is most easily appreciated by comparing successive conditions in which relative rate of reinforcement was constant: 1-2, 2-3, 3-4, 4-5, 7-8, 8-9, and 11-12, for which there are only two counterinstances in 28 comparisons. The role of rela-
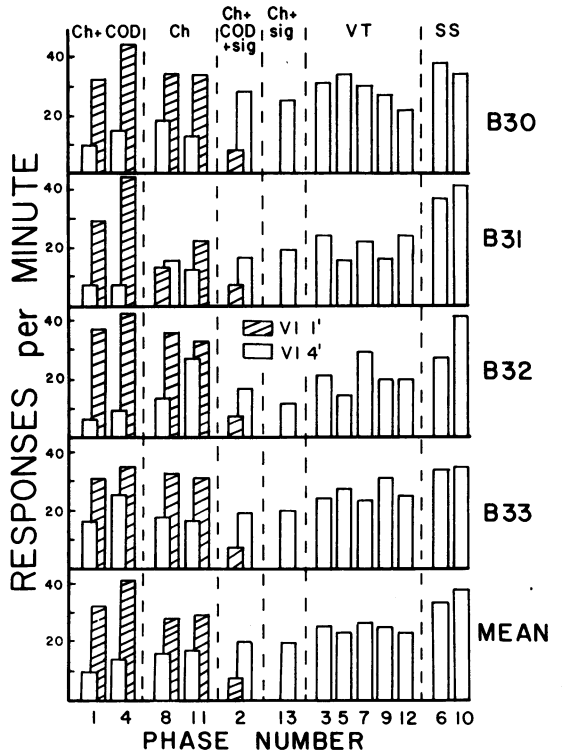

Fig. 1. Response rate (total responses to a key/total session time [less hopper time]) for the VI 1-min (hatched bars) and VI 4-min schedules (unfilled bars) for four subjects and the group mean as a function of condition. Vertical dashed lines group similar conditions. Data are from the last five sessions of each condition.

tive reinforcement is clearly shown in the last two panels (*VT* and *SS*): There was no responding to the VI 1-min key, yet rates to the VI 4-min schedule when presented alone (*SS* condition) were higher than when there was a concurrent VT 1-min schedule (*VT* condition).

Figure 2 presents the median response rates to the VI 1-min and VI 4-min keys during Phases 4 through 13. The dependent variable, which is the reciprocal of the median interresponse time (IRT), is defined by recording responding in terms of IRT distributions. Since IRT distributions were added to our programs only after Phase 3 was completed, the first three phases are excluded from presentation in the figure.

Experimental conditions are presented in Figure 2 in the same order as in Figure 1. As in Figure 1, median rates to the VI 1-min schedule were highest in the *Ch+COD* phase and next highest in the *Ch* phase. However, unlike Figure 1, the median rates to the VI
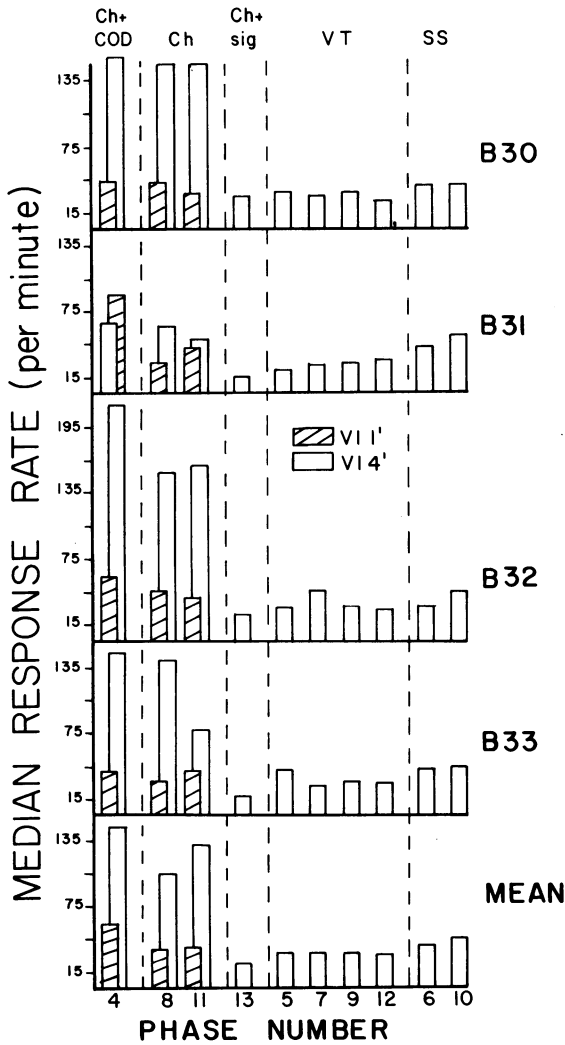
Fig. 2. Median response rate (reciprocal of median interresponse time) on VI 1-min (hatched bars) and VI 4-min schedules (unfilled bars) for four subjects and the group mean as a function of condition. Vertical dashed lines group similar conditions. Data are from the last five sessions of each condition.

Fig. 3. IRT distributions in .1-sec classes on VI 4-min schedule in *Ch* procedure (left side) and *Ch+sig, VT*, and *SS* procedures (right side) for each bird. Data are from the last five sessions of each condition. See text for other details.

Table 2

Relative frequency of VI 1-min (VT 1-min) reinforcement.

Phase Number	Condition	Bird 30	Bird 31	Bird 32	Bird 33	Mean
1	Ch+COD	.804	.832	.852	.828	.829
2	Ch+COD+sig	.808	.788	.796	.784	.794
3	VT+del	.824	.832	.796	.848	.825
4	Ch+COD	.832	.836	.844	.800	.828
5	VT+del	.776	.788	.764	.776	.776
7	VT	.800	.820	.816	.832	.817
8	Ch	.792	.800	.776	.840	.802
9	VT	.784	.776	.796	.776	.783
11	Ch	.768	.804	.832	.804	.808
12	VT+lit	.792	.804	.820	.832	.812
13	Ch+sig	.812	.796	.768	.804	.795

4-min key were also highest during the two choice conditions. Median rates were more than halved in the other conditions, although the *SS* phase rates were consistently higher than the *VT* and *Ch+sig* rates.

Figure 3 amplifies on the median rate data in Figure 2 by presenting IRT distributions for the VI 4-min key during the *Ch* (Phase 11), *Ch+sig* (Phase 13), *VT* (Phase 12), and *SS* (Phase 10) conditions for each bird. A comparison of left- and right-side panels shows that IRT emission during the *Ch+sig, VT*, and *SS* conditions is easily distinguished from
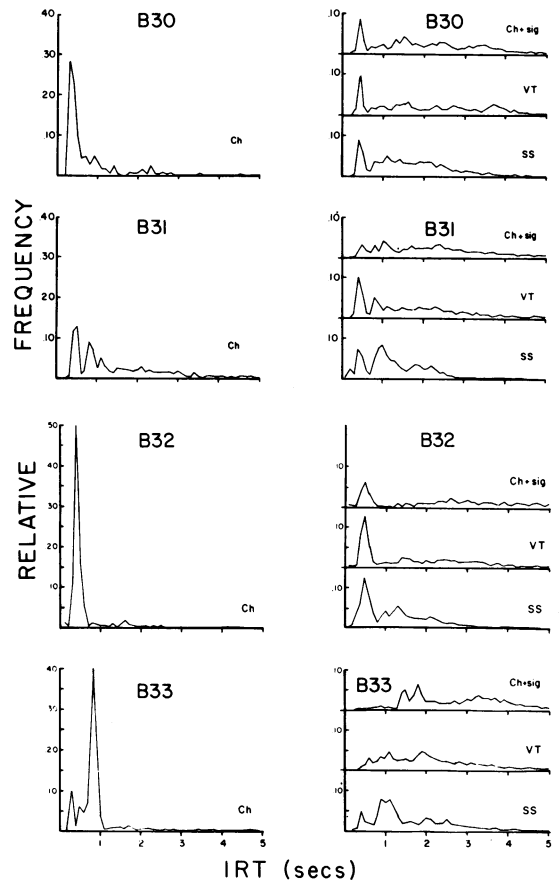
the *Ch* condition: Except for B31, high rates of concurrent responding generate high fre-

quencies of short IRTs (*Ch* condition); however, when the concurrent response requirement is low, the frequency of short IRTs is substantially less (other conditions).

Table 2 presents for all conditions the relative VI 1-min reinforcement frequencies obtained. As is apparent from the table, the relative reinforcement frequency was essentially invariant across conditions except for the *SS* phases, where obviously all reinforcement was provided by the VI 4-min schedule (thus these phases are eliminated from the table).

DISCUSSION

The equation for simple action (Equation 1) is closely related to the matching law (Herrnstein, 1961). This law states that

$$\frac{R_1}{R_1 + R_2} = \frac{r_1}{r_1 + r_2} \quad \text{(Equation 2)}$$

where 1 and 2 are subscripts designating each of two alternatives from a choice procedure. In the years since its formulation, Equation 2 has been successfully applied to data from many different choice procedures (see de Villiers, 1977). When its predictive successes are joined with those of the equation for simple action, one is witness to a parsimonious characterization of behavior that accounts for a wide range of single- and concurrent-schedule performances (Baum, 1974; de Villiers & Herrnstein, 1976).

Both the matching law and the equation for simple action quantify performance within the context of choice, attributing response-rate changes to changes in relative reinforcement rates. This integration of single- and concurrent-schedule effects presupposes they are governed by the same psychological process. That this presupposition has merit is suggested by the many demonstrations that these matching-based equations unify what might otherwise appear to be qualitatively different rate effects produced by unrelated types of schedules.

Despite the parsimony of account and breadth of predictive adequacy offered by these formulations, the data from the present study question whether single-schedule and concurrent-schedule performances can be so integrated. One basis for skepticism is provided by the IRT-based measures presented in Figures 2 and 3. There we can see that the procedures of this study can be split into two categories on the basis of IRT emission to the VI 4-min key: concurrent-operant procedures (high rates) and single-operant procedures with or without extraneous reinforcement (low rates). This dichotomy is not suggested by the equation for simple action, which assumes single-operant procedures with extraneous reinforcement are really concurrent-operant procedures where only one operant can be directly recorded. Were this hypothesis true, single-operant procedures with extraneous reinforcement should generate IRT distributions comparable to those seen in conventional choice procedures. That instead these rates look like those in the *SS* condition (see Figure 3) suggests that single-operant procedures, whether or not they provide extraneous reinforcement, are controlled by a common process distinguishable from that governing choice in concurrent-operant procedures.

We are arguing for a qualitative difference in behavior structure between single- and concurrent-operant procedures. We attribute this difference to differences in how probability of reinforcement varies as a function of time between changeovers for choice vs. single-operant situations: When responding to a single VI schedule, the absence of substantial temporal lapses in responding insures that the probability of reinforcement is essentially constant as a function of time. This is not so when animals respond concurrently. Every time a bird chooses the VI 1-min key, it stops responding to the VI 4-min key, producing a lapse during which the probability of reinforcement for the first response to the VI 4-min schedule increases. Because birds spend four times as long responding to the VI 1-min schedule as the VI 4, the lapses are necessarily four times as large on the VI 4. As a consequence, the probability of reinforcement for a changeover to the VI 4-min schedule is much higher than thereafter.

As stated elsewhere (Silberberg & Ziriax, in press), it is this high local reinforcement probability for the changeover that generates the high proportion of short IRTs often seen on the lean schedule of choice procedures (e.g., Silberberg & Fantino, 1970). And this result is not a direct consequence of concurrent

schedules. Rather, it is due to the competition between concurrent operants these schedules support.

Significantly, our account stresses response, not reinforcer interaction, in accounting for the different patterns of responding seen in procedures with high concurrent responding (e.g., *Ch* procedure) vs. those without (e.g., *VT*, *SS* procedures). In so doing, we question the view inherent in Equation 1 that behavioral output, at least defined in terms of IRTs, can be captured in a formulation defined exclusively in terms of relative rates of reinforcement. As the data from Figure 3 suggest, the rate of alternative reinforcement may be a less important determinant of IRT emission than the rate of alternative responding.

Even though these data suggest the equation for simple action falsely categorizes single-operant procedures within the rubric of choice, neither IRT nor median-rate data can prove this point. The problem is that the predictions of Equation 1 are expressed not in terms of median rates or IRTs, but in terms of a more molar measure—the mean rate of response (responses/session time). To conclude that responding in single-operant procedures should be distinguished from responding in concurrent-operant procedures, differences in mean response rates must also be evident between these two types of procedures.

This evidence is provided in Figure 1, where response rate to the unchanged VI 4-min key is shown to be influenced by two variables: rate of alternative reinforcement and rate of alternative responding. Compare first the *VT* and *SS* conditions where the effects of reducing alternative reinforcement are not contaminated by changes in alternative response rate. Here we see that reducing alternative reinforcement increases the VI 4-min response rate just as the equation for simple action predicts. Next, consider all conditions presented in the figure except the *SS* condition. These conditions all have the same relative reinforcement frequency (see Table 2), a consequence of which is that the equation for simple action predicts that the VI 4-min response rate will be invariant. Yet this prediction is clearly not supported by the data. Instead, manipulations that lead to rate reductions to the altered schedule produce rate increases to the unchanged VI 4-min key.

At the least, these results show the equation for simple action erred in defining behavioral output solely in terms of relative reinforcement rates. As Figure 1 demonstrates, rate to the VI 4-min key is a function of both alternative reinforcement and alternative responding. Future attempts to quantify behavioral output in terms of matching principles should take these dual sources of control into account.

One last issue needs to be addressed: Why do our results differ from Catania's given that so many features of our study were borrowed from his? We suggest that his results might have been due to a subtle confound in his design. Reducing response rate to an alternative by signaling reinforcer availability may have two effects which counteract each other: (1) it may reduce interference with responding to the unsignaled key; and (2) it may increase the value of the signaled alternative by reducing the response cost of producing its reinforcer. The reduction in response interference should yield a rate increase to the unsignaled alternative, whereas the increase in value of the signaled key should, according to the matching law, reduce rates to the unsignaled key. If these opposed effects of signaling reinforcer availability were equal, Catania's findings could have been predicted even though they would not have demonstrated what he thought—the independence of concurrent operants.

With this "balance" hypothesis in mind we replicated Catania's study with different schedule values, the rationale being that these changes would disrupt any balance between the effects of altering response interference and the relative value of the two schedules. That our results differ from Catania's supports our interpretation that these processes were counterpoised, although obviously we do not claim the present study serves as an experimental test. What we claim, however, is that the generality of Catania's finding of response independence is now suspect: Neither our study nor that of Guilkey et al. replicated his major finding that rate to an alternative is governed solely by the relative rate of reinforcement. Rather, response rate seems to be a joint function of relative response rate and relative reinforcement rate.

This outcome, plus the demonstration in the IRT data of a probable process difference between single- and concurrent-performance schedules, argues that any future formulation

of behavioral output must take into account the effects of one response on another.

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