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BEHAVIOR-DEPENDENT REINFORCER-RATE CHANGES IN CONCURRENT SCHEDULES: A FURTHER ANALYSIS

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Six pigeons were trained on concurrent variable-interval schedules in three different procedures. The first procedure was a standard concurrent schedule, and the relative reinforcer frequency for responding was varied. The second was a schedule in which a relative left-key response rate (over a fixed period of time) exceeding .75 produced, in the next identical time period a higher reinforcer rate on the right key. If this criterion was not exceeded, equal reinforcer rates were arranged on the two keys in this period. This was the dependent procedure. In the third (independent) procedure, the periods of higher right-key reinforcer rates occurred with the same probability as in the second procedure, but occurred independently of behavior. In the second and third procedures, the fixed-time period (window) was varied from 5 s to 60 s, and to 240 s in the second procedure only. Performance on the two keys was similar in the concurrent and independent procedures. The procedure used in the dependent conditions generally affected performance when the windows were shorter than about 30 s. Models of performance that assume that subjects do not discriminate changes in local relative reinforcer rates cannot account for the data. Moreover, existing models are inherently unable to account for the effects of contingencies of reinforcement between responding on one alternative and gaining reinforcers on another that are arranged or that emerge as a result of time allocated to alternative schedules. Undermatching on concurrent variable-interval schedules may result from such emergent contingencies.

Key words: concurrent schedules, generalized matching, variable-interval schedules, momentary maximizing, melioration, key peck, pigeons

Vaughan (1981) reported an experiment in which pigeons' relative time allocation on concurrent schedules in a 4-min window affected both the relative and absolute reinforcement rate in the subsequent 4-min window. Despite this contingency, both the ratios of responses emitted and times allocated to the schedules closely matched the ratios of obtained reinforcer frequencies (Vaughan's Figure 8). From these data, Vaughan was able to show that his subjects were not maximizing their overall obtained reinforcer rates. The fact that performance changed between the two conditions of his experiment showed also that the performance of the pigeons was not controlled by minimizing deviations from matching. One theory, melioration, was consistent with the results. This theory (Herrnstein & Vaughan, 1980) states that animals allocate more time to currently higher local reinforcer-rate alternatives. If this process is unconstrained, this ultimately results in an equality between relative choice and relative obtained reinforcers—termed strict matching.

Silberberg and Ziriax (1985) investigated a procedure that was a simplification of that used by Vaughan (1981). Instead of allowing relative and overall reinforcer rates to change relatively continuously with preference in a time window, they arranged just two or three pairs of contingencies depending on preference. For instance, in their Conditions 3 and 8, if relative right-key time allocation in a window was greater than .25, the next window provided equal concurrent variable-interval (VI) schedules that arranged 12 reinforcers per hour (VI 300 s). If relative right-key time allocation was less than .25, then the next window had VI 300 s on the left key but VI 6 s on the right key.

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Silberberg and Ziriax (1985) arranged two window durations, one of 4 min (the same as used by Vaughan, 1981) and one of 6 s, to test whether the subjects in procedures like this, although not molar maximizing, might be maximizing at a more molecular level. They pointed out that, in Vaughan's (1981) procedure, the long delay between emitting a particular relative choice in one window and the consequences in the next window might well lead to a failure in learning the contingency. The 4-min window data that they collected essentially replicated Vaughan's results. However, with the 6-s window (Condition 6), the times allocated to the two alternatives were much less sensitive to changes in the obtained relative reinforcer rates than they were with the longer window duration. Silberberg and Ziriax carried out a simulation of the results using a molecular maximizing model, and suggested on this basis that such an account could describe the results from both window durations.

Silberberg and Ziriax's (1985) paper produced some debate. Vaughan (1987) questioned both the adequacy and the precision of Silberberg and Ziriax's theory and the meaning of the data used to support their theory. At the heart of this last question are the data on the distribution of relative time allocation within windows, and whether the obtained distributions resulted more from the size of the windows than from the contingencies of reinforcement. As Vaughan pointed out, short windows will naturally produce distributions of relative time allocations that peak at the extremes of 0 and 1.0.

The reason we carried out the present experiment was that much of the discussion following Silberberg and Ziriax's (1985) paper required data for its resolution that were simply not available. Vaughan (1981) provided no molecular data because none were directly relevant to the question he asked. Silberberg and Ziriax provided some data on the relative time allocations within windows, but not enough to demonstrate the adequacy of the theory they espoused. Further, although Silberberg and Ziriax reported data from two window durations, these were of very different lengths, and we saw a need to investigate the effects of intermediate window durations to gain some idea of the change in behavior between these two extremes. Finally, we were motivated by a simple question: When window durations are short, do the contingencies arranged lead to the leaning of a behavioral strategy that satisfies, at least partially, the contingencies that more responding on one alternative leads to more reinforcers on the other alternative? If this does occur, as Silberberg and Ziriax suggested, then naturally the matching of time (or response) ratios to obtained reinforcer ratios will be unlikely. Moreover, if such contingencies control performance, then the overall performance will cease to be homogeneous over time, and models such as melioration or molecular maximizing may simply be inappropriate for understanding the behavior. Under the long-window conditions, do the subjects rather discriminate a change in the distribution of reinforcers produced perhaps by chance, and, in this case, quickly follow the change that is produced? Again, this would produce nonhomogeneous performance, and the suggested models would be inappropriate. Such questions require more molecular data, and more control conditions, than have been reported previously. In particular, they require conditions in which the change in relative reinforcer rates occurs noncontingently, but as frequently as in an experimental condition in which the schedule change occurred contingently.

We arranged three types of experimental conditions: (a) concurrent-schedule conditions in which we varied the relative reinforcer rates over a wide range (concurrent conditions), (b) conditions similar to Silberberg and Ziriax's (1985) Conditions 3 and 8, with window durations ranging from 5 s to 240 s (dependent conditions), and (c) conditions with the same window durations as the conditions in (b) above, in which transitions into higher reinforcer-rate windows were noncontingent but occurred with the same frequency as in the parallel condition in (b) (independent conditions).

The present experiment differed from the two previous experiments in a number of ways. First, the preference measure that controlled the conditions of reinforcement in the next window were, in the present experiment, relative response rate rather than relative time allocation, as in Vaughan (1981) and Silberberg and Ziriax (1985). We used dependently arranged concurrent schedules in a (vain) attempt to control the relative reinforcer rates in each of the two types of windows. Silberberg and Ziriax did not mention this aspect of their

procedure (we presume independent scheduling as the default), and dependent scheduling would have been inappropriate in Vaughan's experiment. The timer controlling the window duration operated for only 2 s after each response in both Vaughan's and Silberberg and Ziriax's experiments; here, the timer controlling window duration operated at all times except during reinforcement. Vaughan used a procedure in which a reinforcer could not be produced by a response if no response had been emitted in the 1-s period before that response. This provided a differential reinforcement of high-rate contingency for responding on both keys. This procedure was not used by Silberberg and Ziriax and was not used here. To promote the independence of the responses to the concurrent schedules, a 3-s changeover delay (Herrnstein, 1961) arranged that a response on a key could not be reinforced, even though a reinforcer had been arranged by the schedule, until this time had elapsed after changeover. Neither Vaughan nor Silberberg and Ziriax used such a procedure, but it is routinely used in concurrent-schedule research. Finally, in most conditions of the present experiment, the contingencies in operation at the start of the session were equal-schedule contingencies. Vaughan commenced his sessions at the point on the feedback function that had been in operation at the end of the previous session. Silberberg and Ziriax did not mention this aspect of their procedure, but the numbers of reinforcers obtained (their Table 2) suggest that sessions started in equal schedules.

In a major departure from the previous experiments in this area, we collected the time (at a resolution of 0.01 s) of all responses, all reinforcers, and all window commencements in all experimental conditions.

METHOD

Subjects

The subjects were 6 homing pigeons deprived to 85% ± 15 g of their ad-lib body weights. They were numbered 11 to 16. Bird 13 died after Condition 13, and the data from this bird are not reported here. The pigeons had previously served in concurrent-schedule experiments, so no key-peck or schedule training was required. They had free access to grit and water in their home cages.

Apparatus

The experimental chamber (300 mm wide by 330 mm deep by 330 mm high) was situated remote from a PDP 11/73® computer that controlled all experimental events using a SuperSKED® program. There were three response keys (20 mm in diameter) set 70 mm between centers and 260 mm from the grid floor on one wall of the chamber. Beneath the center key, and centered 130 mm from the grid floor, was an aperture (50 mm high by 50 mm wide) that gave access to a food magazine containing wheat. During reinforcement, the magazine was raised, the grain was illuminated, and the bird was able to eat for 3 s. Only the outer left and right keys were used in this experiment, and when responses to these keys were counted, the keys were illuminated white. During reinforcement, and before and after the session, they were blacked out. There was no other source of illumination in the chamber.

Procedure

A VI schedule was arranged on each of the operative keys. The schedules were constant-probability schedules. Unless a reinforcer was being delivered, every 1 s a probability gate decided whether a left-key reinforcer should be arranged (with a probability $p(L)$) (Table 1). If not, a second gate immediately decided whether a right-key reinforcer should be arranged. There were two different probabilities of right-key reinforcers (in most conditions). These are $p(R_a)$ and $p(R_b)$ in Table 1. Which of these was in effect in any particular window depended on the subject's behavior. If either a left- or a right-key reinforcer had been arranged, both schedules stopped timing; otherwise another 1 s was timed, and the probability gates were again interrogated. When a reinforcer was obtained, the schedules continued timing from the end of the 3-s reinforcer. Sessions ended after 40 reinforcers had been obtained or after 44 min, whichever occurred sooner. A changeover delay (Herrnstein, 1961) was arranged so that 3 s had to elapse before a response could be reinforced following a changeover.

As mentioned above, the right-key probability of reinforcement (per second) depended on the subject's behavior in some conditions. These conditions are called dependent conditions. This procedure was arranged in the fol-

Table 1

Sequence of experimental conditions, probability of reinforcement (per second) on the left and right keys, type of procedure (D = behavior dependent, I = behavior independent, C = concurrent schedule), window duration, and number of sessions.

Condition	Probability/second			Type	Window (s)	Sessions
	$p(L)$	$p(R_a)$	$p(R_b)$			
1[a]	.003	.003	.167	D	5	21
2[a]	.003	.003	.167	D	240	27
3	.003	.003	.167	D	240	25
4	.003	.003	.003	C	240	31
5	.003	.003	.167	I	5	32
6	.003	.030	.030	C	5	25
7	.027	.006	.006	C	5	27
8	.006	.027	.027	C	5	28
9	.030	.003	.003	C	5	24
10	.016	.016	.016	C	5	32
12	.003	.003	.167	D	5	20
13	.003	.003	.167	I	5	26
14	.003	.003	.167	D	10	27
15	.003	.003	.167	I	10	23
16	.003	.003	.167	D	20	20
17	.003	.003	.167	I	20	28
18	.003	.003	.167	D	30	19
19	.003	.003	.167	I	30	30
20	.003	.003	.167	D	60	21
21	.003	.003	.167	I	60	33
22	.003	.030	.030	C	5	31
22b	.030	.003	.003	C	5	16[b]
23	.003	.030	.030	C	5	31

[a] Sessions started in unequal schedules. Otherwise, sessions started in equal schedules.

[b] Condition 22b was a brief reversal, and performance did not become stable.

lowing way. Every fixed period of time ("window" in Table 1), the relative number of responses emitted on the left key $[B_l/(B_l + B_r)]$ was calculated. If this value was greater than .75, $p(R_b)$ was in force during the next window. Otherwise, $p(R_a)$ was in force. In behavior-independent conditions (independent conditions), the production of $p(R_b)$ in a window was independent of behavior and occurred with a fixed probability (calculated from the dependent condition for that subject, with the same window duration) at the start of each window. Finally, some standard concurrent VI VI schedule conditions (concurrent conditions) were arranged. In these, relative behavior in a window did not affect relative reinforcer rates because $p(R_a) = p(R_b)$.

We used our standard stability criterion to determine when experimental conditions should be changed. After each session, the relative left-key response rate was calculated. When 10 sessions had been completed, median relative response rates over five sessions were calculated, and if the medians of adjacent but nonoverlapping sets were within .05 of each other for a subject, a minor stability criterion had been reached. When all subjects had reached such a minor criterion five, not necessarily consecutive, times, the experimental conditions were changed for all subjects. These criteria required a minimum of 14 sessions to be satisfied.

The sequence of experimental conditions is shown in Table 1. The experiment started, in Conditions 1 and 2, with a replication of Silberberg and Ziriax's (1985) Conditions 3-S and 8-M (5-s and 240-s windows, respectively). $p(L)$ was .003, $p(R_a)$ was .003, and $p(R_b)$ was .167. The sessions in these conditions also commenced with $p(R_b)$ arranged on the right key. This aspect of the procedure is probably different from that used by Silberberg and Ziriax, and these were the only two conditions to start in unequal schedules. Condition 3 was a further replication of Silberberg and Ziriax's Condition 8-M, in which sessions commenced in equal schedules. Condition 4 used $p = .003$ for all schedules. In all the above conditions, reinforcer-rate changes were behavior dependent. Condition 5 arranged the same probability of a schedule change after each 5-s window that had been obtained in Condition 1 (5-s window), but the changes occurred independently of the relative frequency of responses in the previous window. Individually, the probabilities ranged from .236 to .395 every 5 s.

Conditions 6 to 10 arranged standard concurrent VI VI schedules, with a 5-s window recording but not operating. In these conditions, the total arranged reinforcer rate was .036 per second. No data were obtained from Condition 11 following a minor programming error.

Conditions 12 to 21 investigated the effect of window durations from 5 s to 60 s on performance when $p(L)$ was .003, $p(R_a)$ was .003, and $p(R_b)$ was .167. The sessions started in equal schedules, and pairs of conditions were arranged. In the first of each pair, the reinforcer-rate change on the right key was dependent on a relative left-key response rate of greater than .75 in the previous window. In the second condition of each pair, reinforcer rates changed independently of behavior at the

end of each window with a probability that was calculated (for each subject) from the dependent condition. Windows longer than 60 s were not investigated, because it was found in Condition 3 (240-s window) that subjects very infrequently produced the higher reinforcer rates on the right key.

Condition 22 was a replication of Condition 6, the first concurrent-schedule condition arranged. Condition 22b, which lasted 16 sessions, was a brief reversal of Condition 22, and the data for this condition are not reported here. Finally, Condition 23 was a further replication of Conditions 6 and 22.

RESULTS

Left and right response and reinforcer frequencies were summed over the last five sessions of each condition. The first analysis done on these data was to regress log response and time ratios against log reinforcer ratios as is appropriate for a fit to the generalized matching law. This was done using least squares linear regression. The slope of the relation is the sensitivity to reinforcement, and the intercept is the bias. The results of these regressions, for each individual subject, are shown in Table 2 according to the three types of conditions arranged here (concurrent, or changes in conditions of reinforcement that were either dependent on, or independent of, preference). The data averaged over the group are shown in Figure 1. Data from Conditions 1, 2, 4, and 5 were not shown or analyzed because, for one reason or another, they did not fit easily in the main sequence of results.

For the concurrent-schedule conditions (6 to 10 and 22 and 23), individual sensitivities to reinforcement varied from 0.66 to 0.93 (response measures) and between 0.88 and 1.26 (time measures). Four of the 5 subjects showed greater time-allocation sensitivities than response-allocation sensitivities. This difference between response- and time-allocation slopes is regularly found in concurrent VI VI schedules, although usually in arithmetic schedules instead of the exponential schedules used here (Taylor & Davison, 1983). The fits for each subject, as evidenced by the standard errors of the slope estimates, were very good. Intercept (log bias) values were generally close to zero as expected, although Bird 12 had a consistent bias toward the left key.

Table 2

Results of least squares linear regression analyses according to the generalized matching law. %VAC is the percentage of data variance accounted for by the fitted line.

	Responses			Time		
Bird	Slope (*SE*)	Intercept	% VAC	Slope (*SE*)	Intercept	% VAC
Concurrent schedules						
11	0.78 (0.03)	−0.08	99	0.93 (0.03)	−0.06	99
12	0.66 (0.08)	0.13	92	1.02 (0.07)	0.20	97
14	0.93 (0.03)	0.16	100	0.88 (0.04)	0.00	99
15	0.76 (0.03)	0.05	99	1.26 (0.04)	0.05	99
16	0.92 (0.04)	0.03	99	0.98 (0.04)	0.06	99
Independent reinforcer-rate changes						
11	0.59 (0.12)	−0.23	86	0.95 (0.15)	−0.10	91
12	1.16 (0.20)	0.51	90	1.01 (0.19)	−0.02	87
14	0.79 (0.08)	0.03	96	0.79 (0.12)	−0.02	92
15	0.66 (0.18)	0.20	76	0.99 (0.20)	0.08	86
16	0.80 (0.09)	−0.03	95	0.97 (0.10)	0.04	96
Dependent reinforcer-rate changes						
11	0.08 (0.14)	−0.28	8	0.25 (0.29)	−0.31	16
12	0.62 (0.21)	0.09	69	0.44 (0.34)	−0.21	29
14	0.29 (0.20)	−0.07	35	0.39 (0.12)	−0.15	71
15	0.01 (0.02)	−0.07	4	0.16 (0.05)	−0.14	68
16	0.12 (0.11)	−0.22	22	0.23 (0.18)	−0.19	30

In the odd-numbered conditions from 13 to 21, when the reinforcer schedules on the right key changed independently of behavior, log response- and time-allocation measures were very similar to those obtained in the concurrent schedule conditions (Figure 1, Table 2). As Table 2 shows, response allocation sensitivity was between 0.59 and 1.16, and time-allocation sensitivity between 0.79 and 1.01. The fits of the generalized matching law were apparently less good than for the concurrent-schedule conditions, but, as Figure 1 shows, in these conditions log response ratios varied over only about half the range of the variation in the concurrent-schedule conditions. On a sign test, the difference between the estimated sensitivity values from the concurrent and independent conditions was not significant. The variation in the log reinforcer ratio that did occur in the independent conditions happened because of the decreasing arranged probabilities of entering the unequal, higher, reinforcer-rate schedules when the window duration was increased. This trend moved the obtained reinforcers on the two keys closer to equality. There were some rather large biases (e.g., Birds 11, 12, and 15) for response measures, but none for time measures.

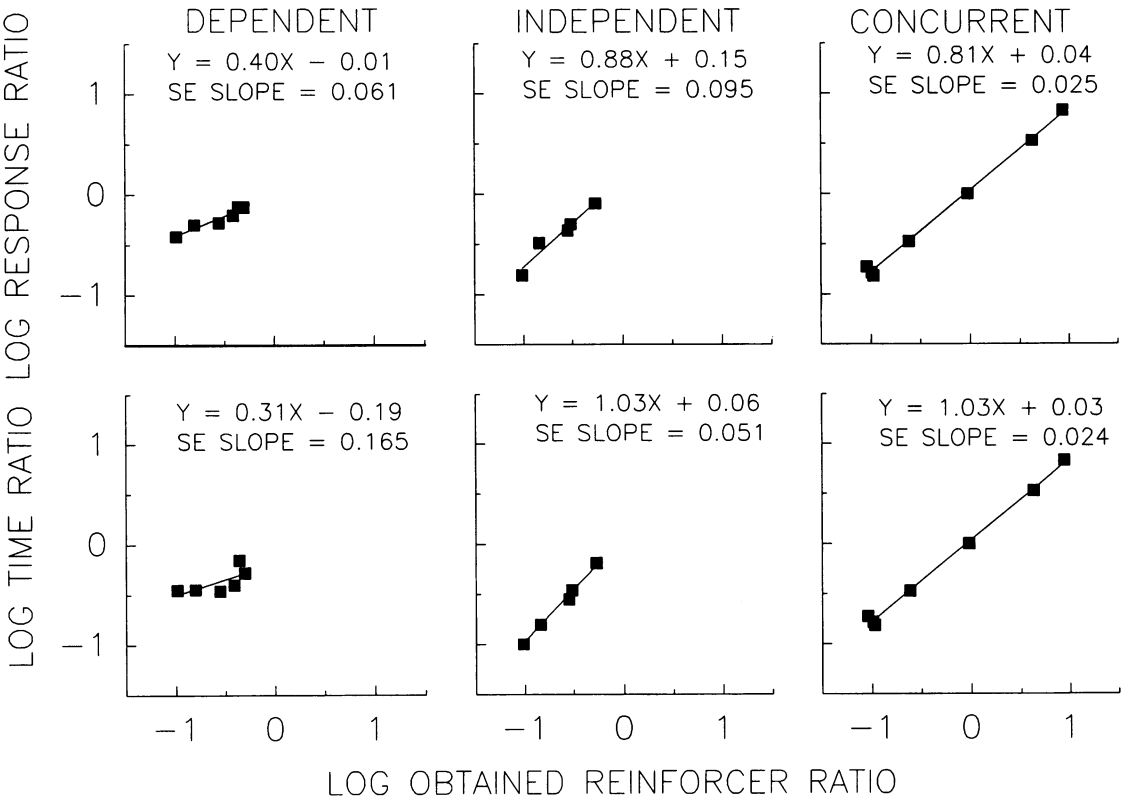

Fig. 1. Log response ratios (upper panels) and time-allocation ratios (lower panels) as a function of log obtained reinforcer ratios in the dependent, independent, and concurrent conditions of this experiment. The data have been averaged over all 5 subjects. The best fitting straight line, its equation, and the standard error of the slope are shown for each measure and set of conditions.

In the conditions that arranged dependent right-key reinforcer-rate changes (3, 12, 14, 16, 18, 20), response-allocation sensitivity varied between 0.01 and 0.62 and time-allocation sensitivity between 0.16 and 0.44. Sensitivities to reinforcement for both measures were all lower in the dependent conditions than in the concurrent or independent conditions for all subjects, so this result is significant on a sign test. As Figure 1 shows, these differences were caused by less extreme response- and time-allocation measures (compared with the concurrent or independent conditions) when the log reinforcer-rate ratio was more negative. The more negative log reinforcer-rate measures were produced by the shorter window conditions, so shorter window durations produced greater deviations from concurrent- or independent-condition performance than did longer windows.

Figure 1 shows that, in the dependent conditions, the obtained reinforcer ratio varied as a function of the window duration. When the window was short, the log reinforcer ratio was strongly negative because the birds entered the high right-key reinforcer rate frequently. But when the window was long, they entered this part of the schedule less frequently, although for a longer time per entry. These effects are displayed in Figure 6 below. Figure 2 compares log ratio measures of responses emitted, time spent responding, and reinforcers obtained in the independent and dependent pairs of conditions as a function of window duration. Over the common range 5 to 60 s, log obtained reinforcer ratios increased in a very similar fashion with increasing window duration, and the measures were similar in the two phases as designed by the procedure. Although log response and time measures in the independent conditions increased in a manner similar to the log reinforcer ratio, these measures did not follow log reinforcer ratios in the dependent conditions when window durations were

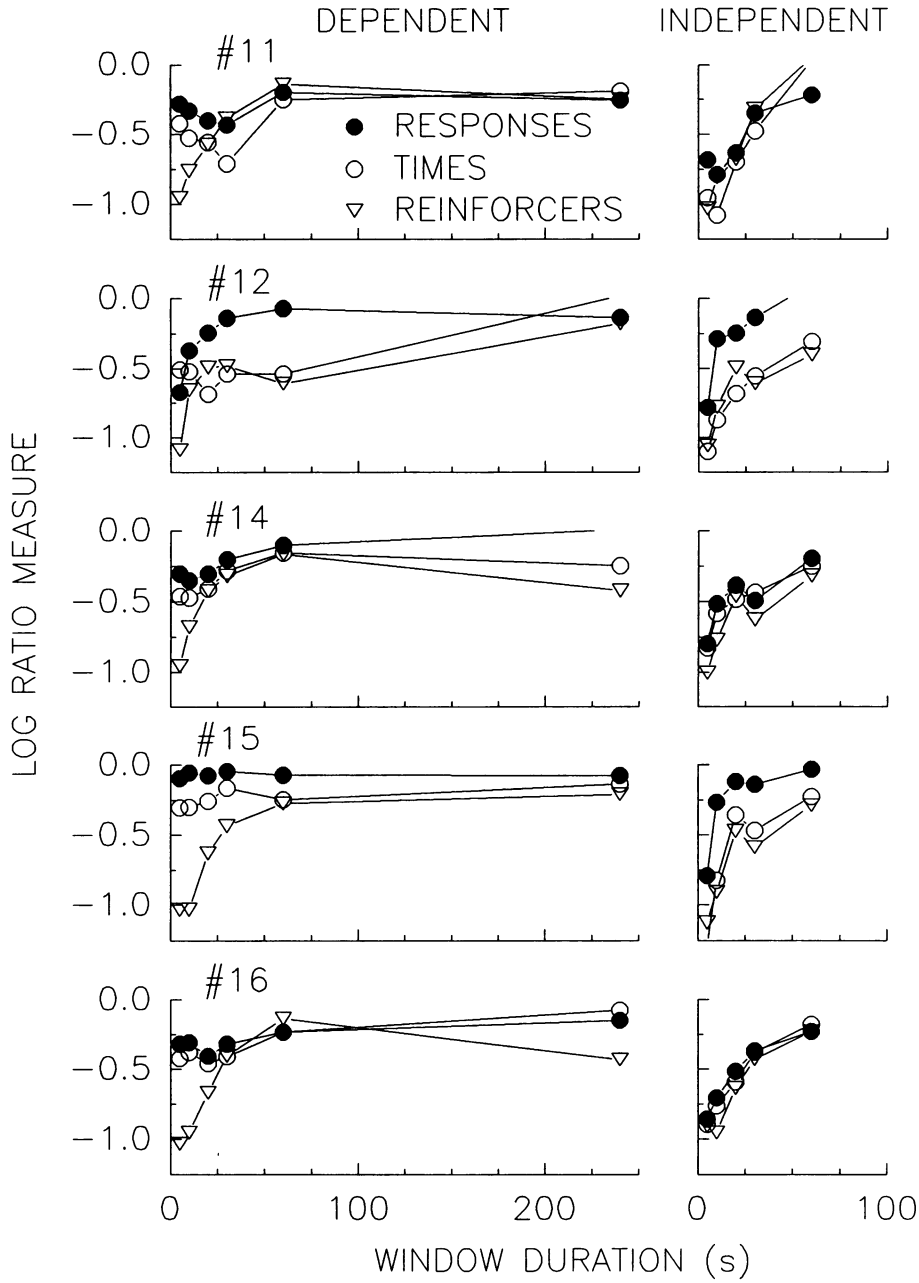

Fig. 2. Log response ratios, time-allocation ratios, and obtained log reinforcer ratios as a function of the duration of the window in the dependent and independent conditions. Note that some data points fell off the graph.

shorter than 60 s (Birds 14, 15, and 16) or 30 s (Birds 11 and 12). Bird 12 showed a clear decrease in log response ratios with decreasing window durations, similar to its performance in the independent conditions, but it showed no such similarity in log time ratios. Notice that, at short window durations, log response- and time-allocation ratios in dependent conditions were generally less negative than log reinforcer ratios, representing the undermatching already noted (Figure 1).

Figure 3 shows the differences between log

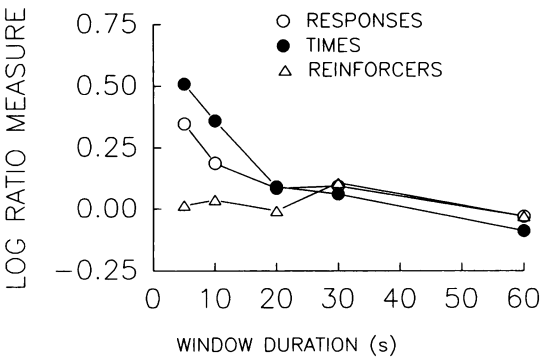

Fig. 3. The difference between log response, time, and reinforcer ratios in the dependent and independent conditions as a function of window duration. The data have been averaged over the 5 subjects.

response, time, and reinforcer ratios in the dependent and independent phases for each window duration that was common to these phases. These data have been averaged over all 5 birds. First, log reinforcer ratios were generally similar (apart from being slightly higher in the dependent phase at the 30-s window), showing that the procedure of arranging a probability of entry into the unequal-schedule windows that was the same as that obtained in the equivalent dependent phase led to similar obtained reinforcer ratios in the two phases. The differences shown in Figure 3 did not, therefore, result from differing reinforcer ratios between the phases. As expected from previous research (Silberberg & Ziriax, 1985), window duration had a profound effect in the dependent procedure compared with the independent procedure when the windows were 5 s and a decreasing effect as the windows were lengthened, with the difference being eliminated on average by about 30 s. Time allocation appeared to be more affected than response allocation even though the dependent contingency acted on the latter.

The dependent and independent phases did not differ in the distribution of reinforcers in time—in both procedures, reinforcers either occurred every 6 s or every 600 s on average on the right key. Both these distributions of reinforcers in time between windows differed, however, from the exponential schedules arranged in the concurrent-schedule conditions. The present finding that there was no significant difference between the molar performance of the independent- and concurrent-schedule phases (Figure 1, Table 2) suggests that the distribution of reinforcers in time does not markedly affect sensitivity to reinforcement, as has been suggested by Taylor and Davison (1983).

Consistent with the claim of Silberberg and Ziriax (1985), performance in dependent conditions deviated more from performance in concurrent or independent conditions when short windows were arranged. Comparing Conditions 6 (concurrent schedule), 13 (independent phase), and 12 (dependent phase), which had similar obtained reinforcer ratios and window durations, Condition 12 (the dependent condition) had much higher relative response and time measures. This indicates rather clearly that the contingency in Condition 12 was affecting behavior, and that the bird did not enter the high right-key reinforcer-rate window simply by chance (cf. Vaughan, 1987). Indeed, assuming that the subjects did follow right-key reinforcer-frequency changes by their behavior, relative left-key response rates *when the equal schedules were in effect* in Condition 12 (and other dependent conditions) would be even higher than shown in Figure 2. Such questions, though, can be better answered from more molecular analysis of performance in these and other conditions.

The similarity in performance between the concurrent-schedule and the independent phases, and the difference between both of these and the dependent phase, is also evident in Figure 4, in which the interchangeover times (ICTs) on each key are plotted as a function of the relative obtained reinforcer rate. The concurrent and independent phases show the usual concurrent-schedule functions (e.g., Tustin & Davison, 1979). In the dependent phase, however, the subjects remained on the right key for very short times even when the reinforcer rate on that key was, overall, much higher than that on the left key. Interchangeover times are plotted as a function of window size for the independent and dependent conditions in Figure 5. Left-key ICTs increased as a function of window size in both types of conditions. As Figure 4 shows, this was due to the change in obtained reinforcer rates in the independent phase, and the similarity in this measure between the dependent and independent phases suggests that the left-key ICTs in the dependent phase might also

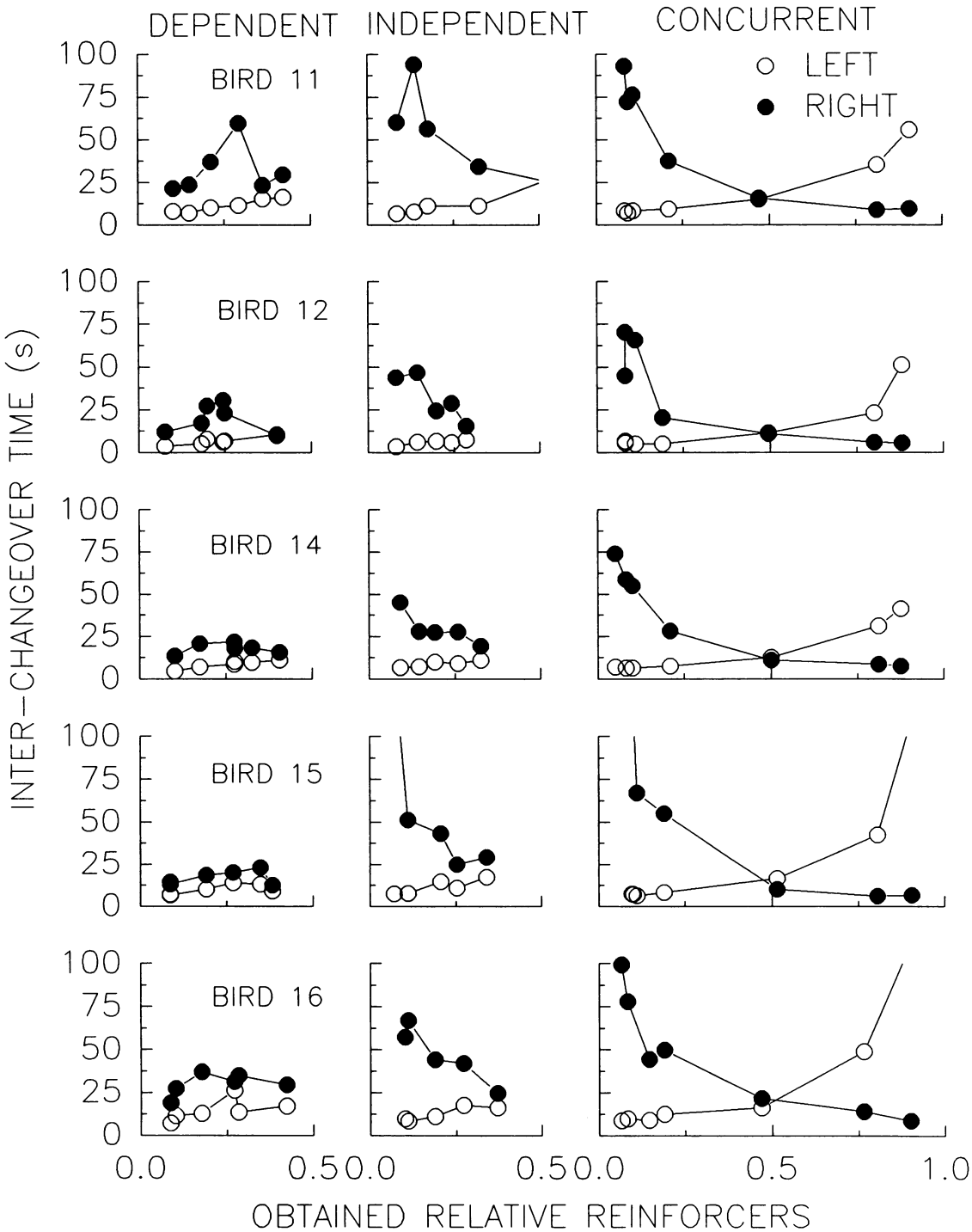

Fig. 4. Interchangeover times (in seconds) on the left and right keys as a function of relative obtained reinforcer rates in the dependent, independent, and concurrent conditions. Note that some data points fell off the graph.

be controlled by changes in relative reinforcer rates. The right-key ICTs in the dependent phase at first increased with increasing window duration up to 10 s (Bird 14), 20 s (Birds 12 and 16), 30 s (Bird 11), or 60 s (Bird 15) and then decreased, with these ICTs becoming similar to those in the independent phases. These results again suggest that the dependent contingency applied under short windows does affect performance, but control is lost with long windows (Silberberg & Ziriax, 1985).

Figure 6 shows the probability of meeting the 75% left-key contingency within a window in the various phases of the experiment for each subject. For the concurrent-schedule conditions (with an arbitrary 5-s window), the probabilities are shown as a function of relative reinforcer rates obtained. In these conditions, the probability was very low when the left key gave one tenth the reinforcer rate of the right key and rose steeply as relative reinforcer rates increased. The probabilities for the dependent and independent conditions are shown as a function of window duration. In the dependent conditions, the probability was high when the window was 5 s and decreased sharply (with some reversals for different individuals) as the window was extended. Given that the obtained relative reinforcer rates in Condition 12 (dependent, 5-s window) were similar to those obtained in concurrent Conditions 6, 22, and 23 (which appear on the far left of the concurrent-schedule graph in Figure 6), it is evident that the frequency of satisfying the contingency is not simply a by-product of the distribution of behavior produced by the obtained reinforcer distribution (cf. Vaughan, 1987). Further, when the window was 240 s (as used by Vaughan, 1981, and by Silberberg & Ziriax, 1985), the probability of satisfying the contingency was effectively zero. Again, we see that lengthening the window decreases control by the contingency. In the independent conditions, the probability of satisfying the contingency did not change in any clear direction as the window was extended. The comparison of these independent and dependent results again suggests that relative responding in the dependent conditions was directly affected by the contingencies between preference and subsequent reinforcement conditions.

In light of Vaughan's (1987) discussion, it is clearly of interest to investigate relative response rates emitted within windows in more detail, and Figure 7 shows the relative frequency of different relative left-key response rates emitted in the concurrent conditions averaged across subjects. The graphs in this figure are ordered top to bottom, left to right, according to increasing relative reinforcer rates on the left key. The performances in Conditions 22 and 23 (replications of Condition 6) have been omitted because they produced distributions very similar to those obtained in Condition 6. The distributions in Figure 7 were obtained from the 5-s windows arranged in (but ineffective in) the concurrent-schedule conditions. The distributions showed a number of features. The major effect was that the frequencies of relative response rates less than .05 and greater than .95 always made up the bulk of the events. When the reinforcer rate was higher on the left key, almost all relative left-key response rates were greater than .95, and when it was higher on the right key, most were less than .05. The frequency of relative response rates between these two extremes was always low, but was greatest when the schedules were equal (Condition 10). Evidently, with standard concurrent-schedule performance, analysis at the level of a 5-s window produces extreme distributions of preference.

Figure 8 shows the same data, but analyzed according to a 4-min window (that is, 48 successive 5-s windows, ignoring all data from any incomplete 240-s window at the end of sessions). These distributions were centered at, or close to, the sessional relative response rates plotted in log ratio form in Figure 1. Clearly, the duration of the window used for analysis has, as Vaughan (1987) suggested in his commentary, a profound effect on distributions of relative response rates, and this difference will overshadow the effects of the contingencies that use these windows. Useful comparisons may only be made between the behavioral effects

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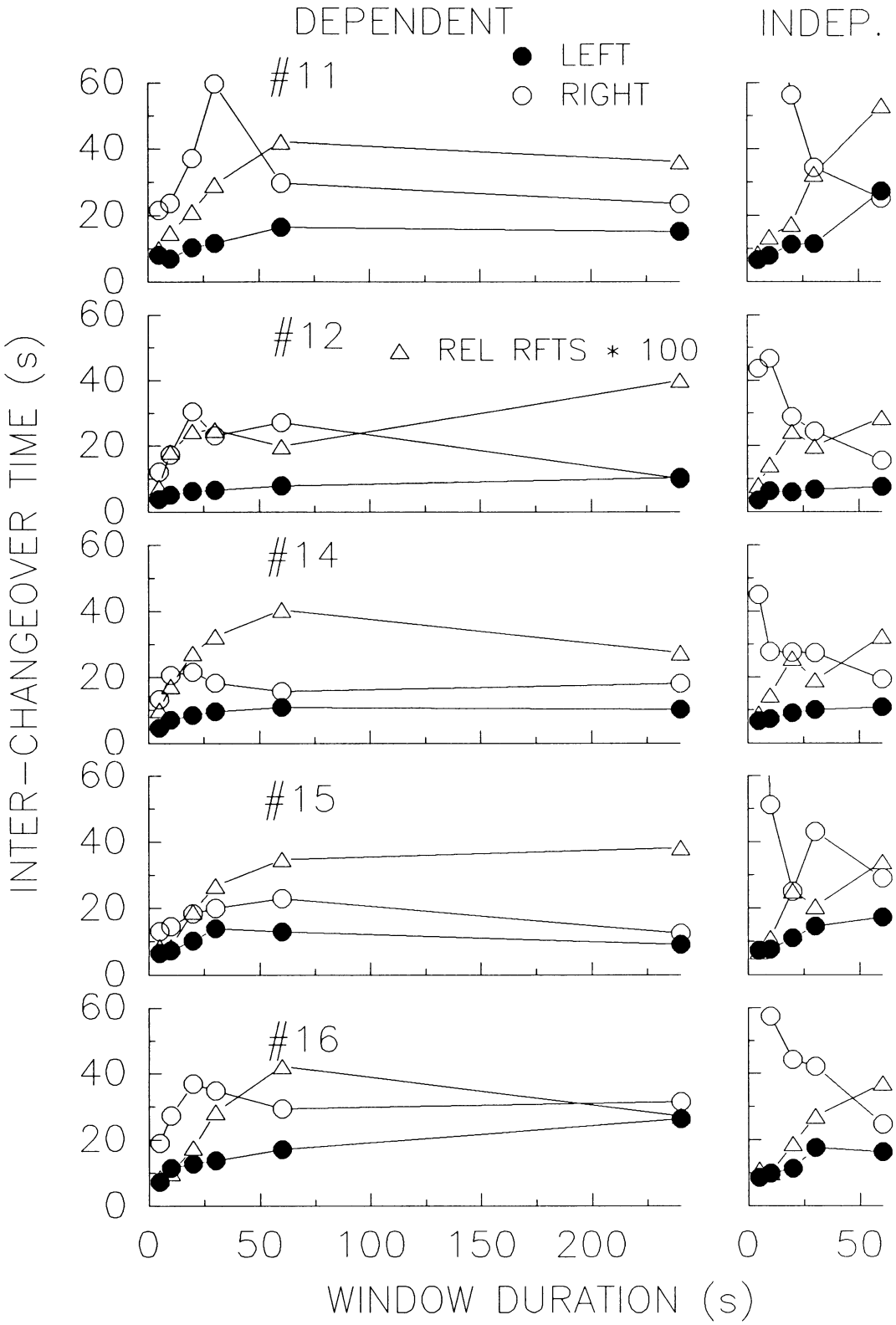
Fig. 5. Interchangeover times (in seconds) and relative obtained reinforcer rates as a function of window duration in the dependent and independent phases.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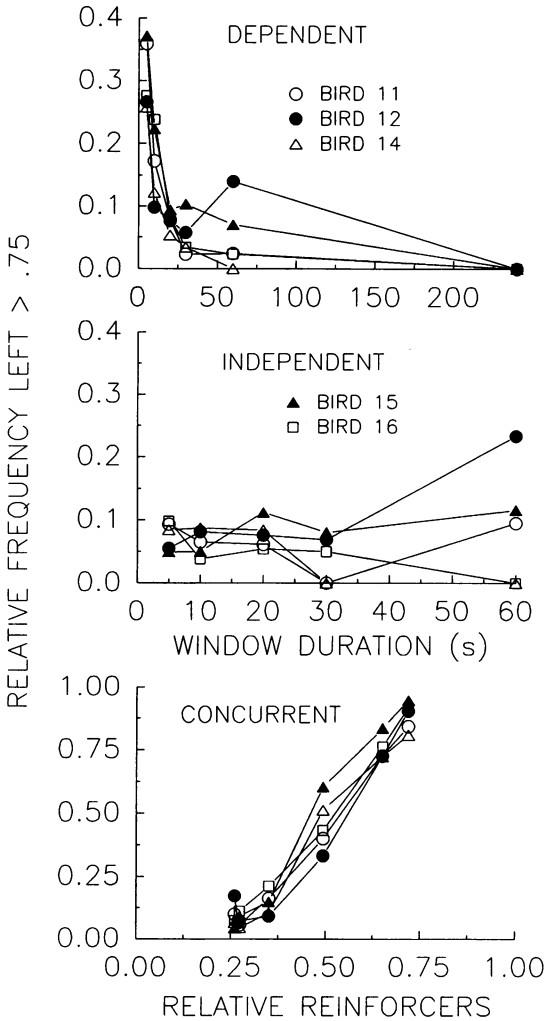

Fig. 6. The probability of satisfying the criterion of relative left-key responses greater than .75 in a window as a function of the window duration for the dependent and independent conditions, and as a function of the relative reinforcer rate for the concurrent conditions for each subject.

of arranging different window durations if the sampling durations used in the *analysis* of such data are the same.

Figure 9 shows the distributions of relative response rates in the independent conditions. As the window duration increased from 5 s to 60 s (and, concomitantly, as the relative reinforcer rate moved toward .5), the distribution changed from being strongly peaked in the range 0 to .05 (as in Condition 6, Figure 7) to a distribution that peaked at .5. In other words, as the window duration increased, performance changed from being similar to that in concurrent-schedule Condition 6 (Figure 7, 5-s window) to being one similar to that in concurrent-schedule Condition 10 (Figure 8, 240-s window). The discussion above shows that this change probably is a result only of sampling with different window durations.

The distributions of relative response rates emitted in windows in the dependent phases according to window duration are shown, pooled over subjects, in Figure 10. When the window was 5 s (Condition 12), the distributions showed peaks at <.05 and >.95, as they did for 3 of the 4 subjects reported by Silberberg and Ziriax (1985). However, the distributions found here were more extreme, possibly due to the changeover delay and slightly smaller window duration used here. As the window duration increased, both of these peaks decreased, and a peak at .5 developed until, at 240 s, the distribution was strongly centered around .5. The distributions for the shortest window (5 s, Condition 12) were noticeably different from those from the independent Condition 13 (Figure 9). In the former, the peak at <.05 was higher and that at >.95 was lower, thus producing more undermatching in Condition 12 than in Condition 13. The 60-s window (Condition 20) produced a distribution that was very similar to that obtained from the independent Condition 21 (Figure 9). At this level of analysis, it is again evident, therefore, that control by the contingency in the dependent conditions decreased as the window increased. As we stated above, comparing distributions with differing window durations is potentially misleading, but clear differences can be seen if independent control conditions are arranged. The performances at 5-s and 240-s window durations were very similar to those reported by Silberberg and Ziriax. We could not argue for an effect of the dependent contingencies (such as shown in Figure 6) on the basis of Figure 10 without the comparison Figure 9.

DISCUSSION

We have already mentioned a number of differences between the procedure used in the present experiment and those used by Vaughan (1981) and by Silberberg and Ziriax (1985). Despite the differences in procedure, the data obtained in the short- and long-duration win-

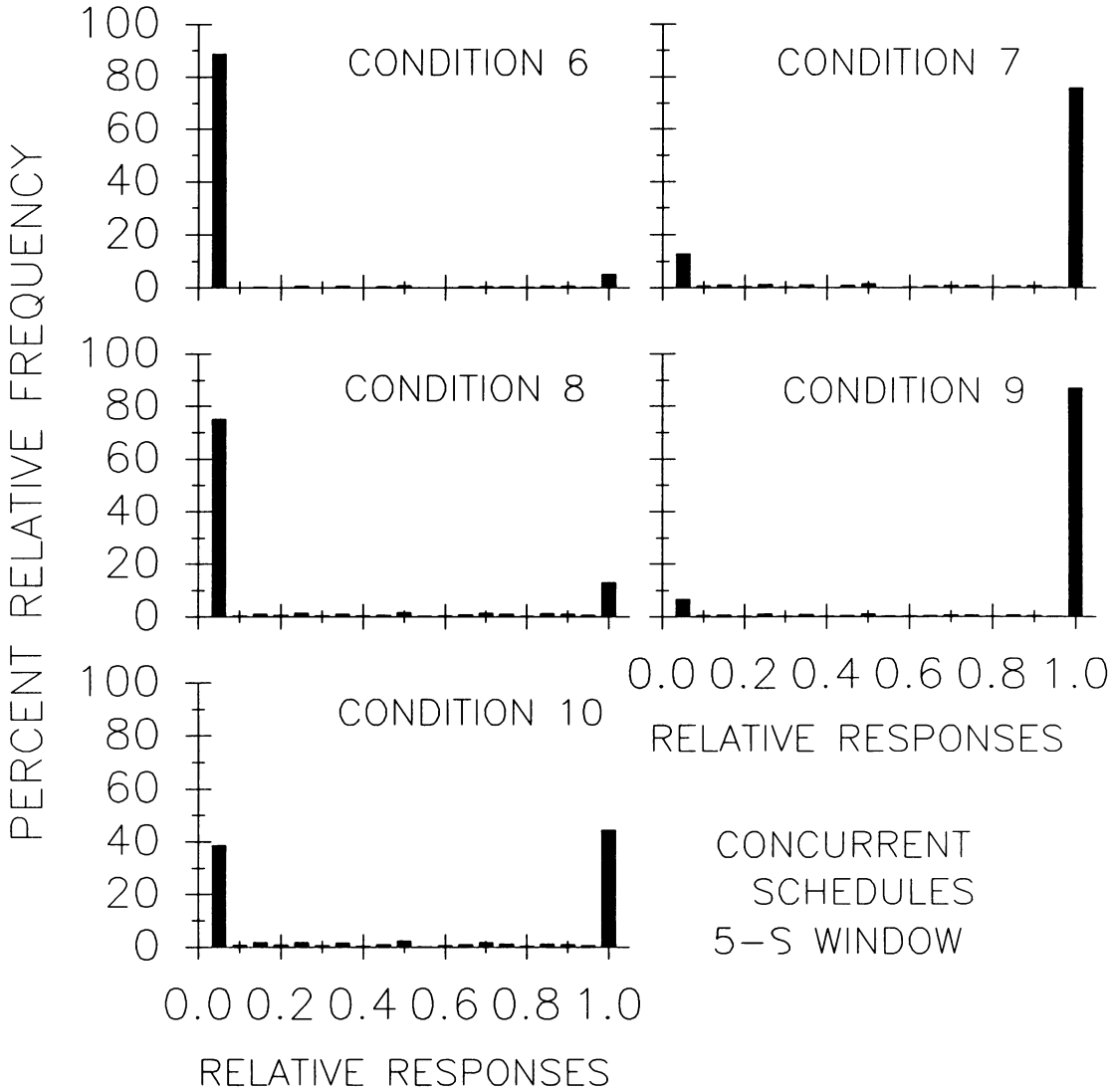

Fig. 7. The relative frequency of emitting relative left-key response rates for Conditions 6 to 10 (concurrent conditions). Reading down the left panel and then down the right panel gives increasing left-key reinforcer rates. The data were analyzed over all 5 subjects using a 5-s window.

dows of the dependent conditions replicated the previous results of Vaughan and of Silberberg and Ziriax very closely indeed. The present results are therefore germane to both the empirical and theoretical questions that have been raised in the area (e.g., Vaughan, 1987).

The detailed analysis of the performance in this experiment showed that, as Silberberg and Ziriax (1985) suggested, effective contingencies between left-key responding and right-key conditions of reinforcement operated when the window durations were short (5, 10, and possibly 20 s), but not when they were longer. Theories of performance, such as melioration (Herrnstein & Vaughan, 1980; Vaughan, 1981), ratio invariance (Horner & Staddon, 1987), momentary maximizing, and molecular maximizing (Silberberg & Ziriax, 1985) will need to be tailored to take account of this time span.

Most current theories are theories of performance in relatively homogeneous temporal environments, although all attempt to account

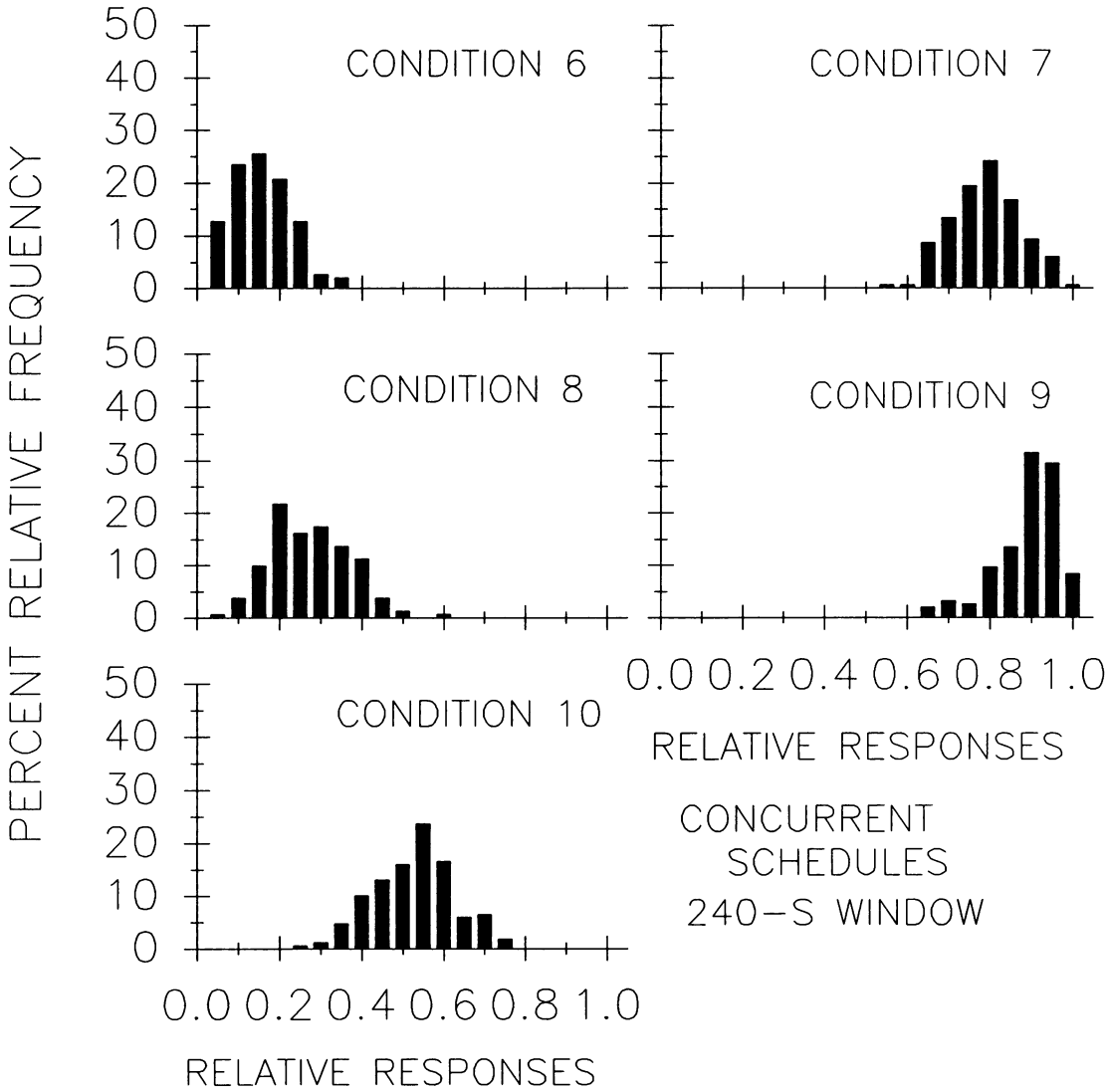

Fig. 8. The relative frequency of emitting relative left-key response rates for Conditions 6 to 10 (concurrent conditions). The data are the same as used in Figure 7, but they were analyzed using a 240-s window.

for the learning of systematic directional changes in environmental conditions. Most theories do not attempt to understand short-term *discriminable* changes in the conditions of reinforcement. The present experiment, and experiments like it (Silberberg & Ziriax, 1985; Vaughan, 1981), do arrange such short-term discriminable changes, and they are of two sorts. First, when a response–reinforcer contingency affects behavior in a short window, the subject probably discriminated through its own behavior that the .75 contingency had been met, and changed over and responded on the right key (see Figure 5, for example). Second, when longer windows are arranged, and the high right-key reinforcer-rate window is entered by chance, subjects discriminated the change in right-key reinforcer conditions and responded more to the right key (see below). When one or both of these sources of control are operative, fast performance changes can occur on window transition; such changes are not addressed by current performance theories that deal naturally only with homogeneous

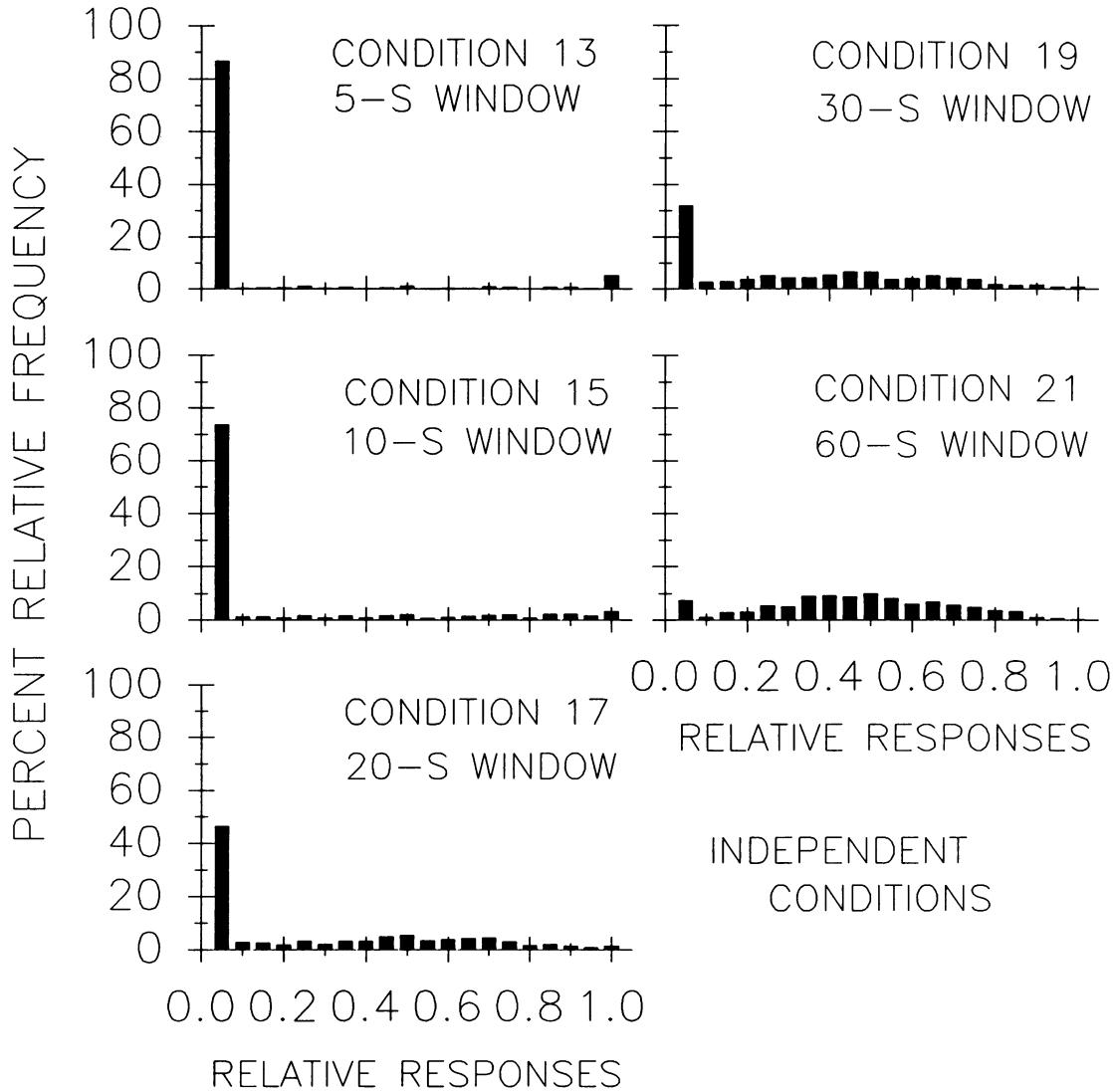

Fig. 9. The relative frequency of emitting relative left-key response rates within windows in independent Conditions 13 (5-s window), 15 (10 s), 17 (20 s), 19 (30 s), and 21 (60 s). The data were averaged over all 5 subjects.

conditions of reinforcement. Thus, it is difficult to see how procedures such as those investigated here can constitute adequate tests of current, rather limited, models of performance. A consideration of stimulus control is surely needed to understand the present data and those of Vaughan and of Silberberg and Ziriax.

Given the stimulus control by changes in reinforcer conditions that occurs when a window with a high reinforcer rate on the right key is entered (such as in longer windows in the independent conditions), it is interesting that these conditions provided, at a molar level, a close approximation to standard concurrent-schedule performance at all window durations. The same comment can be made about the performance in the longer windows in the dependent conditions. If matching performance is unaffected by such runs of reinforcers, then *molar* models of performance do not need to take this aspect of stimulus control into account. "Matching" seems to be an adequate molar description of performance in conditions in which there are no *discriminable dependen-*

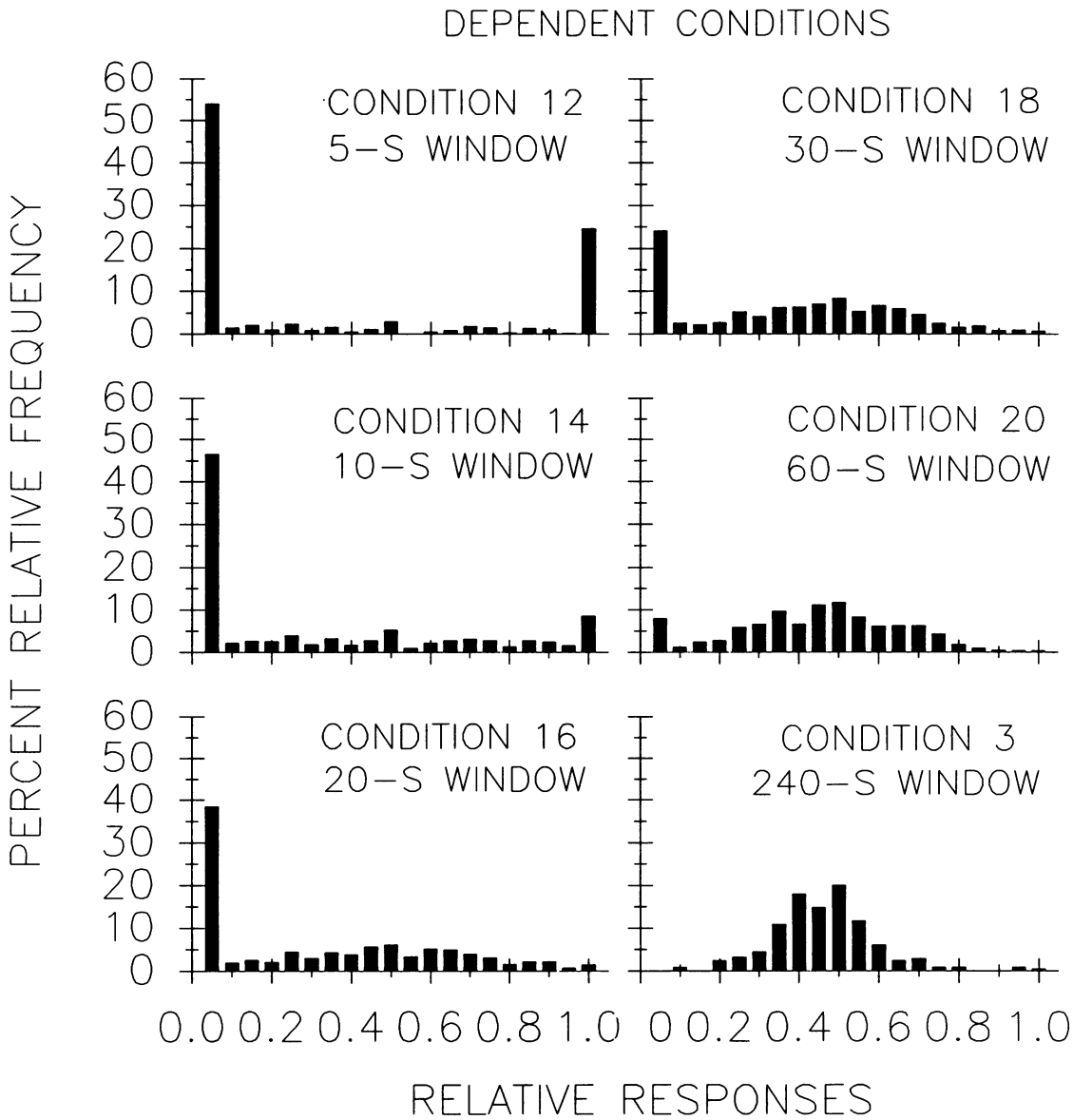

Fig. 10. The relative frequency of emitting relative left-key response rates within windows in dependent Conditions 12 (5-s window), 14 (10 s), 16 (20 s), 18 (30 s), 20 (60 s), and 3 (240 s). The data were averaged over all 5 subjects.

cies between emitting one response and gaining reinforcers for an alternative response. As a theory of matching, melioration seems to describe well session-to-session changes in performance in procedures such as that used by Vaughan (1981). As that theory stands, though, it is not appropriate to apply it to within-session data or to procedures in which local contingencies produce local changes in relative reinforcer rates (as in dependent conditions). Molecular models are designed to account for the local performance and, hence, should account for deviations from homogeneous performance in both the high and low reinforcer-rate windows used here. But without some notion of stimulus control, they are inherently unable to do so. Some of these models (e.g., momentary maximizing, Silberberg & Ziriax, 1985) seem able to make accurate predictions at the molar level, but this is not the level at

which they must be tested. Although molar accuracy is necessary, it is not a sufficient proof of the model.

By their own behavior, subjects working on concurrent VI VI schedules produce the sorts of contingencies that were investigated here and by Silberberg and Ziriax (1985) and by Vaughan (1981). Responding for a longer period on any key increases the probability that a reinforcer will be available on the alternative key. If such contingencies are discriminable—and it is likely they are—then, as we have shown, they will promote undermatching if the contingencies are that responding more on one alternative increases the reinforcer rate on the other. (If the contingency was such that responding more on one alternative increased the reinforcer rate on that alternative, overmatching would likely result.) The possibility exists, then, that behavior allocation is carried out with a sensitivity greater than that normally measured in molar performance on concurrent VI VI schedules. Perhaps this sensitivity is 1.0, as sensitivity in concurrent fixed-ratio schedules is trivially 1.0, and there can be no contingency of the type investigated here in concurrent ratio schedules. Such a notion would be consonant with Baum's (1974) view that sensitivity is nominally 1.0, but that various artifacts or emergent contingencies arising from the subject's interaction with the schedules generally bring it below this level.

The emergent contingencies that exist between responses on one alternative and reinforcers on the other can be shown by analyzing the responses emitted and reinforcers obtained before and after windows in which relative left-key responses were greater than .75. Figure 11 shows such an analysis of data for all subjects in three conditions that provided similar overall relative left-key reinforcer rates: Conditions 6 (concurrent), 12 (dependent), and 13 (independent). All these conditions used 5-s windows. Window 0 was the one in which the criterion was met. The concurrent and independent conditions provided much the same results: In Windows 3 and 2, relative response rates were usually strongly toward the right key and were below the overall sessional level. In the independent and concurrent conditions, this is followed in Window 1 by an increase in left-key responding, consistently above sessional averages, and, for Birds 14 (independent) and 16 (independent and concurrent), to an increase in relative right-key reinforcers to above the sessional average. This process resulted in the criterion being met in Window 0, indicating that a run of mainly left-key responses had occurred. This run continued, to some extent, into Window 1, and it was followed by a period (Windows 2, 3, and usually 4) in which right-key responses and reinforcers predominated and relative left values were substantially below sessional averages. In this analysis, the performance of Bird 16 was anomalous, with high rates of relative left-key reinforcers preceding high relative rates of left responses. This bird's performance was therefore following an obtained change in relative reinforcer frequency within about 10 s of its occurrence. But Bird 16 showed a similar pattern of relative responses and reinforcers following the meeting of the response criterion. Recall, though, that there was no contingency to respond left for right-key reinforcers in these conditions.

The dependent condition gave quite a different result. Prior to meeting the criterion, relative responses were generally closer to indifference than relative reinforcers (undermatching), although, like the concurrent and independent analyses, relative left reinforcers often exceeded their prevailing value in Window 1, perhaps both resulting from the operation of the dependent contingency, and simultaneously helping to produce satisfaction of the criterion in Window 0. Relative response and reinforcer rates were close to their prevailing values in Window 1, suggesting (as did Figure 5) that the left-key response runs generally exceeded the 5-s window duration. Then, in Window 2, almost every reinforcer was obtained on the right key, and relative left-key response rates fell to a low level. In Windows 3 and 4, relative response rates usually regained, or even exceeded, their prevailing values, and relative reinforcer rates had normally regained their sessional values in Window 4 (exceeding that value for Bird 15). Compared with the independent and concurrent conditions, the dependent conditions thus showed relatively truncated runs of left-key responses, as was shown in the ICT analysis in Figure 5. But, despite the differences between the dependent conditions on the one hand and the independent and concurrent conditions on the other, the latter types of conditions did provide contingencies similar to the former—a run of

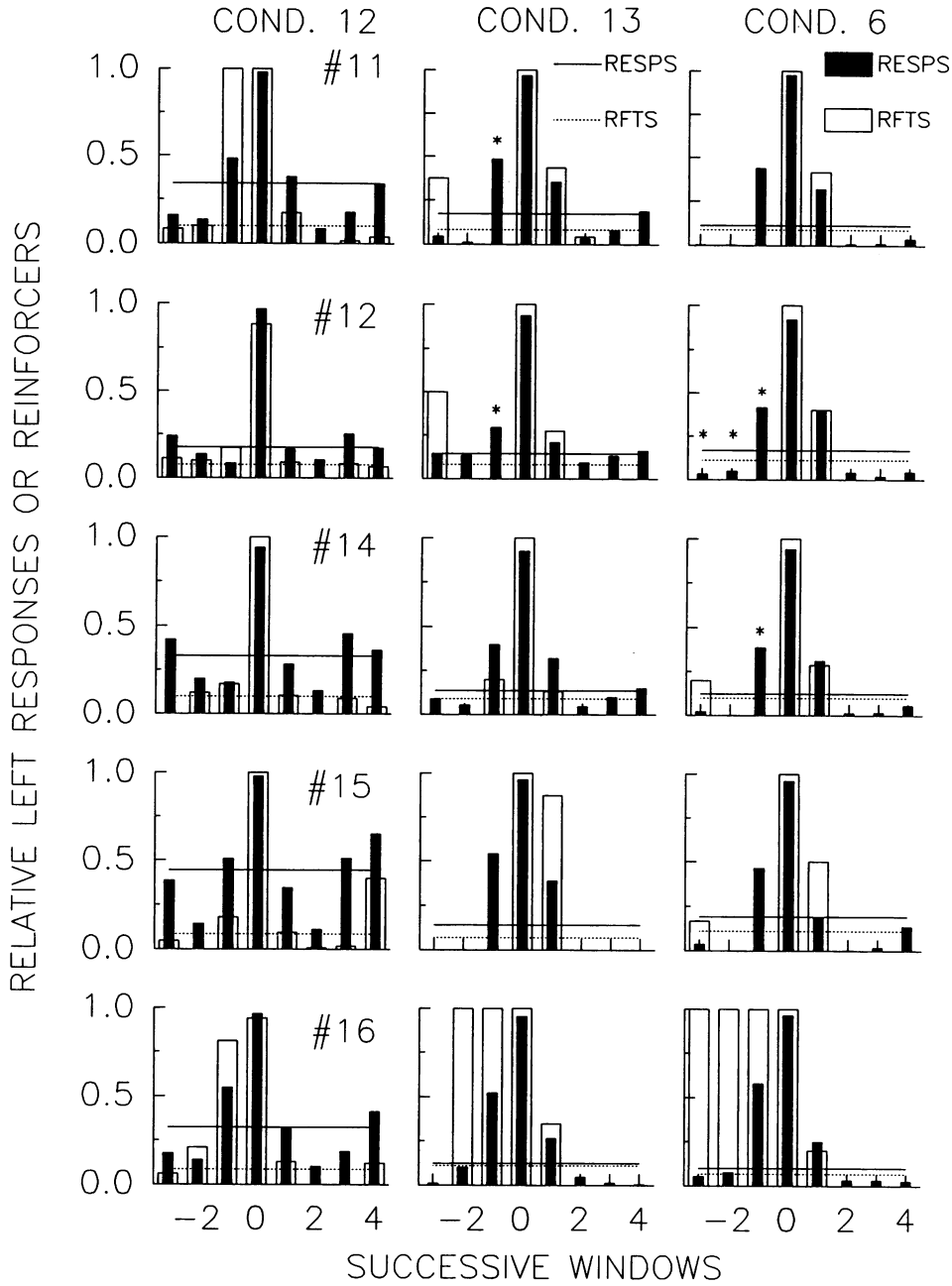

Fig. 11. Relative response and reinforcer rates prior to and following a window (Window 0) containing a relative left-key response rate of greater than .75 in Condition 12 (dependent condition), 13 (independent condition), and 6 (concurrent condition). These conditions were selected because they provided similar obtained relative reinforcer rates. The continuous horizontal line shows the overall relative response rate, and the broken line shows the overall relative reinforcer rate.

responses on the left key subsequently produced higher-than-prevailing reinforcer rates on the right key. Indeed, the postcriterion effects in the latter conditions were, if anything, more extreme than in the former.

Proving that the subjects detected these emergent contingencies, and responded accordingly, is difficult. But some evidence bears directly on this possibility. Shull and Pliskoff (1967; see the reanalysis by Davison & McCarthy, 1988) showed that increasing changeover delays up to 20 s progressively increased sensitivity to reinforcement. We interpret this as the progressive elimination of the discrimination of emergent contingencies between responding on one key and reinforcement on the other—the usual interpretation of changeover-delay effects. But when Shull and Pliskoff reduced the changeover delay from 20 s to 0 s, sensitivity remained high. Our interpretation is that the emergent contingencies were not reasserted, probably because each changeover-delay duration was arranged normally for only five sessions.

We have called these properties of concurrent schedules *emergent* because they arise from the transaction of the subject's behavior with its environment. The effects will be to some extent self-amplifying, because a longer time spent responding on one alternative will, in concurrent VI VI schedules, increase the likelihood of the behavior resulting in a reinforcer on the other alternative. But they will also be self-limiting: If the time spent responding on an alternative exceeds the sorts of limiting values found here (20 to 30 s), the subsequent alternative reinforcer is, according to the present results, unlikely to be effective in maintaining such a long ICT. Generally, then, as the reinforcer rate on a key is increased and the ICTs on this key increase, the marginal rate of reinforcers for long ICTs will decrease, presumably promoting undermatching.

Evidently, the contingencies arranged in the short-window dependent conditions had a very strong effect on performance, much greater than that usually seen on concurrent schedules. The reason for this lies in the differing nature of the contingencies. In the dependent conditions, the additional contingency arranged was discrete with a clear criterion-relative left response rate in the window being required. The emergent properties of concurrent schedules that we discussed above are continuous rather than discrete. That is, there is a continuous relation between the length of a run of responses on a key and the probability that a reinforcer will be available on the alternative schedule. We suspect that such continuous relations will have, in general, less effect on performance than discrete relations because continuously varying contingencies will be less discriminable to the subject.

REFERENCES

Baum, W. M. (1974). On two types of deviation from the matching law: Bias and undermatching. *Journal of the Experimental Analysis of Behavior,* **22,** 231–242.

Davison, M., & McCarthy, D. (1988). *The matching law: A research review.* Hillsdale, NJ: Erlbaum.

Herrnstein, R. J. (1961). Relative and absolute strength of response as a function of frequency of reinforcement. *Journal of the Experimental Analysis of Behavior,* **4,** 267–272.

Herrnstein, R. J., & Vaughan, W., Jr. (1980). Melioration and behavioral allocation. In J. E. R. Staddon (Ed.), *Limits to action: The allocation of individual behavior* (pp. 143–176). New York: Academic Press.

Horner, J. M., & Staddon, J. E. R. (1987). Probabilistic choice: A simple invariance. *Behavioural Processes,* **15,** 59–92.

Shull, R. L., & Pliskoff, S. S. (1967). Changeover delay and concurrent schedules: Some effects on relative performance measures. *Journal of the Experimental Analysis of Behavior,* **10,** 517–527.

Silberberg, A., & Ziriax, J. M. (1985). Molecular maximizing characterizes choice on Vaughan's (1981) procedure. *Journal of the Experimental Analysis of Behavior,* **43,** 83–96.

Taylor, R., & Davison, M. (1983). Sensitivity to reinforcement in concurrent arithmetic and exponential schedules. *Journal of the Experimental Analysis of Behavior,* **39,** 191–198.

Tustin, R. D., & Davison, M. (1979). Choice: Effects of changeover schedules on concurrent performance. *Journal of the Experimental Analysis of Behavior,* **32,** 75–91.

Vaughan, W., Jr. (1981). Melioration, matching, and maximization. *Journal of the Experimental Analysis of Behavior,* **36,** 141–149.

Vaughan, W., Jr. (1987). Reply to Silberberg and Ziriax. *Journal of the Experimental Analysis of Behavior,* **48,** 333–340.

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