MATCHING, MAXIMIZING, AND THE BEHAVIORAL UNIT: CONCURRENT REINFORCEMENT OF RESPONSE SEQUENCES

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Pigeons pecked two keys in a probability matching situation in which four two-peck sequences were intermittently reinforced: left-left, left-right, right-left, and right-right. In Phase 1, relative reinforcement rate was varied with respect to the first response of a sequence: reinforcers were differentially assigned for left-left and left-right sequences as opposed to right-left and right-right sequences. The second response of reinforced sequences occurred equally on the left and right keys across conditions. In Phase II, relative reinforcement rate was varied for sequences that involved an alternation as opposed to those that did not. The relative outputs of the different sequences matched the relative reinforcement rates for the different sequences in both phases. Relative response rates for key pecks did not always match relative reinforcement rates. The intertrial interval separating responses was varied in both phases; increases in the intertrial interval affected the relative frequency of different sequences. The results demonstrate that response sequences acted as functional units influencing choice and thus support a structural account of choice. At the same time, the matching of relative sequence proportion and relative reinforcement rate supports a matching account.

Key words: matching, maximizing, behavioral unit, response sequence, molar and molecular views, concurrent schedules, intertrial interval, memory, pigeons

Under concurrent schedules, reinforcers are intermittently produced by two or more responses. A general finding is that the relative distribution of behavior to the different alternatives matches the relative distribution of reinforcers for those alternatives. If, for example, 75% of the reinforcers are delivered for responses to one key, then approximately 75% of the responses will be to that key. This matching relation has been obtained in a variety of situations and has acquired the status of a general law (see de Villiers, 1977, for a review). The matching law has been very important in the learning area and has generated a great number of experiments, a variety of quantitative statements, and different theoretical and explanatory positions (e.g., de Villiers, 1977).

A fundamental question raised in this context concerns the most appropriate way of considering the matching data. Matching is identified when data are averaged over large blocks of time, typically an entire session. Responses to one key are divided by the total number of responses, and the resulting measure is compared to a similar measure for reinforcers. This method of expressing the data averages out moment-to-moment changes in responding (e.g., Menlove, 1975) and does not consider sequential patterns that may exist (e.g., Shimp, 1966; Silberberg, Hamilton, Ziriax, & Casey, 1978). Although this molar analysis ignores some aspects of the data, it has a number of appealing features. It provides a reasonable, quantitative description of performance under a variety of conditions and in many different situations. And, it offers a theoretical framework for the explanation for other concepts, such as response strength (e.g., de Villiers & Herrnstein, 1976; Herrnstein, 1970) and reinforcer value (e.g., Baum & Rachlin, 1969; Killeen, 1972; Rachlin, 1971).

An alternative position emphasizes a more molecular analysis of the data by placing greater emphasis on moment-to-moment changes in behavior. Sequential patterns of responding have been observed in choice situations, and these patterns suggest the possibility of a momentary maximizing process (e.g., Shimp, 1969; Silberberg et al., 1978).

Matching might depend on moment-to-moment changes in maximizing, and the molar matching law might result from averaging over these more molecular changes in performance (Shimp, 1966). A molecular approach to the analysis of choice offers the advantage of a more detailed analysis of the data and also addresses questions relating to the organization of behavior (e.g., Shimp, 1976, 1978, 1979).

Ironically, one aspect of molecular analyses involves a shift in emphasis from the individual key peck or lever press as the unit of behavior to response sequences as the functional units (Shimp, 1975). Observation of sequential response patterns suggests that the functional units in choice situations may not be simply left- and right-key pecks or lever presses; instead the units might be complex sequences of responses. Most of the evidence suggesting that sequences act as units derives from the analysis of sequential dependencies in choice situations (e.g., Shimp, 1966). However, only a few experiments have explicitly reinforced response sequences in choice situations.

Catania (1971) trained pigeons to peck on two keys and reinforced pecking according to a variable-interval schedule, but only after a particular pattern of pecks had been emitted. Only one response pattern was reinforced in each condition, with the required sequence being changed over conditions. Under one set of conditions the reinforced pattern consisted of a peck to Key A preceded by n responses to Key B. Under a different set of conditions different combinations of four pecks to the two keys were required (e.g., AAAA, AABA, ABBA, etc.). Catania did not report data for individual sequences but instead showed data for the absolute and relative numbers of responses to the two keys. Catania found that a greater proportion of B pecks was emitted as the number of B pecks contained in the required sequence increased and that the proportion of B pecks increased when pecks of this sort were required nearer the end of a sequence. Since Catania reported results only for A and B pecks, it is impossible to assess the effects of reinforcement on different, individual sequences (see Grayson & Wasserman, 1979, for a detailed discussion of this matter); however, the results are instructive and indicate changes in behavior when different sequences were reinforced.

Silberberg and Williams (1974) trained pigeons to peck on two keys in a discrete-trials probability-matching situation. Food was given more often for left-key than for right-key responses, but food was only delivered following an alternation from one key to the other. So, although individual key pecks were reinforced with different probabilities, the only sequences of key pecks reinforced were alternations. Silberberg and Williams varied the intertrial interval separating successive pecks and found that the pigeons simply alternated from key to key when the intertrial interval was short. When, however, the intertrial interval was increased, the alternation sequences decreased and were replaced by patterns in which left-key pecks, the pecks directly reinforced, predominated. The results indicate that response sequences may act as functional units of behavior but that there are temporal limitations influencing these units.

Grayson and Wasserman (1979) trained pigeons to emit sequences of two pecks on a discrete-trial procedure. On each trial, a sequence of two pecks produced either a blackout or food. Grayson and Wasserman reinforced only one sequence per condition, reinforcing each of the four possible two-peck sequences under different conditions. They observed that the pigeon emitted primarily the one sequence that was reinforced and only rarely emitted sequences that did not produce food. However, some unreinforced sequences occurred more often than others. When, for example, the reinforced sequence was an alternation (e.g., left-right) the most frequently occurring nonreinforced sequence involved extra pecks like those directly reinforced (e.g., right-right). These findings support the earlier suggestions that sequences can act as functional units and in addition demonstrate how reinforcement of one sequence may affect the output of a variety of sequences.

These previous experiments, as well as others dealing with different but related issues (Gollub, 1977; Hawkes & Shimp, 1975; Wasserman, Nelson, & Larew, 1980; Weisman, Wasserman, Dodd, & Larew, 1980) have provided valuable information about the ways in which sequences can act as units. The present experiment continued in this line of research since sequences rather than individual responses were reinforced. However, our experiment differed from past research in the ways in which

sequences were reinforced. In past experiments, one sequence was reinforced in each condition; in contrast, we arranged food probabilistically for four different two-peck sequences. If sequences act as functional units under normal concurrent schedules, surely different sequences are reinforced and with different frequencies. By reinforcing several sequences, we hoped to approximate more closely the conditions that prevail in conventional choice experiments. Different sequences were differentially reinforced in our experiment through changes in the relative reinforcement rates for individual sequences. The effects of these manipulations were assessed both with respect to individual key pecks and the output of the different sequences. The main point of the experiment was to see how these changes in behavior related to the alternative analyses of choice.

METHOD

Apparatus

The pigeon chamber was an ice-chest type chamber constructed after the design of Ferster and Skinner (1957). A Coleman three-way convertible cooler was used as a side-opening chamber. The work space was approximately 34 cm for each dimension. The interior walls of the cooler were not parallel, so the aluminum work panel was made the following way: the width was 34 cm, the inside vertical height was 33 cm and, the outside 35 cm. Three response keys (Ralph Gerbrands Co.) were located in a horizontal row, 8 cm from center to center, 25 cm above the floor. Each key could be lit by different colored lights from Lehigh Valley Electronics Q-lamps. Food was delivered by a Lehigh Valley Electronics feeder directly below the center response key. The feeder opening was 5.5 cm wide and 5 cm high; the bottom of this opening was 10.5 cm from the floor. A Lehigh Valley Electronics houselight was placed above the center key 30.5 cm above the floor. The floor, walls, and ceiling of the work space were painted with flat black paint (the floor, however, was always covered by wire screen and computer paper). An exhaust fan was attached to the outside of the chamber to provide ventilation and masking noise.

The chamber was housed in a room in which white noise was always present. Sessions were controlled by solid state circuitry (Coulbourn Instruments) located in an adjacent room.

Subjects

The subjects were four adult male Silver King pigeons, maintained at approximately 80% of their free-feeding weights. These pigeons were naive at the start of the experiment. Key pecking was established by a shaping procedure.

Procedure

Sessions, generally conducted six days a week, lasted until a pigeon produced 60 reinforcers. A trials procedure was used. Normally, two response keylights were lit, with red on the center key and green on the right key (the left keylight was always dark). A peck to either key produced a blackout or, intermittently, produced food. During the blackout, which normally lasted .5 sec, the keylights were turned off and responses had no scheduled consequences. Food was produced intermittently, subject to several restrictions. First, a single variable-interval 45-sec schedule controlled food availability. (This schedule was arranged in the manner described by Catania and Reynolds, 1968, and contained twenty intervals.) The pigeons simply emitted a series of responses until food became available; but, even with the variable-interval requirement satisfied, food was not delivered for just any response. Instead food was only produced following completion of one of four two-peck sequences: left-left, left-right, right-left, and right-right. The particular sequence selected for reinforcement was determined by a series of probability gates (one gate for the first peck of a sequence and one for the second). Only the preselected sequence could produce food, the others could not. If, for example, the sequence, LL, had been selected, and the interval requirement had been met, the series of pecks LRRLRLRLL would end in food only after the final left response, which completed the LL sequence. The particular sequence chosen for reinforcement was alternated from reinforcer to reinforcer (Stubbs & Pliskoff, 1969). All four sequences were reinforced, but some were reinforced more often than others in the ways described below.

Phase I. The first series of conditions varied relative reinforcement rate for the four response sequences. There are, of course, many

Table 1

Number of sessions, relative reinforcement rates calculated different ways (see text for details), and intertrial intervals under different conditions.

Condition	Sessions	RELATIVE REINFORCEMENT RATE							INTERTRIAL INTERVALS (in sec)
		SEQUENCES				First Left	Second Left	Alter-nations	
		L-L	L-R	R-L	R-R				
					Phase I				
6	33	.05	.05	.45	.45	.10	.50	.50	.5
7	39	.12	.12	.38	.38	.25	.50	.50	.5
8	26	.25	.25	.25	.25	.50	.50	.50	.5
3	36	.38	.38	.12	.12	.75	.50	.50	.5
2	26	.45	.45	.05	.05	.90	.50	.50	.5
1	67	.38	.38	.12	.12	.75	.50	.50	1
4	30	.38	.38	.12	.12	.75	.50	.50	4
5	27	.38	.38	.12	.12	.75	.50	.50	8
					Phase II				
9	35	.05	.45	.45	.05	.50	.50	.90	.5
10	28	.12	.38	.38	.12	.50	.50	.75	.5
11	29	.12	.38	.38	.12	.50	.50	.75	1
12	36	.12	.38	.38	.12	.50	.50	.75	4
13	21	.12	.38	.38	.12	.50	.50	.75	8

different ways to vary relative reinforcement rate when four sequences are involved. Our way emphasized changes in reinforcement for the first response in a sequence. Table 1 shows the conditions (as well as those of the other parts of the experiment), their order of occurrence, and the number of sessions under each. Over the first five conditions shown in Table 1, relative reinforcement rate increased for left-left and left-right sequences and decreased for right-left and right-right sequences. A consistent feature of these manipulations was a change in relative reinforcement rate for those sequences in which the first peck of a sequence was to the left key. Relative reinforcement rate, calculated with respect to the first peck of a sequence to the left key— (L-L + L-R) / (L-L + L-R + R-L.+ R-R)—, increased from .10 to .90. Although relative reinforcement rate differed for left and right with respect to first peck of a sequence, the second peck was reinforced equally on the left and on the right across all conditions. Relative reinforcement rates, calculated with respect to the second response of a sequence—(L-L + R-L) / (L-L + L-R + R-L + R-R)—, was .50 across all conditions. As a result, the key pecks that actually produced food were equally divided between the left and right keys. Similarly, relative reinforcement rates remained equal across conditions for sequences that involved

alternations (R-L + L-R) and those that did not (L-L + R-R).

Under a second set of conditions, relative reinforcement rate remained constant at .75 for a first left, while the intertrial interval or blackout duration was changed from .5 sec to 1 to 4 to 8 sec.

Phase II. In the first two conditions of Phase II, relative reinforcement rate was varied for sequences involving an alternation. Relative reinforcement rates were increased for left-right and right-left sequences and decreased for left-left and right-right sequences such that the relative reinforcement rate for alternation was .90 and .75. Relative reinforcement rates for the first and for the second response of a sequence were equal for left and right responses.

Under a second set of conditions the intertrial interval was varied between .5 and 8 sec, while relative reinforcement rate for alternations was held constant at .75.

Each condition of the experiment remained in effect until performance was stable, as judged visually, for at least five sessions.

RESULTS

The total number of key pecks to each key was recorded each session as was the total for each two-peck sequence. Sequences were re-

corded in the following way. If, for example, a pigeon pecked right, left, right, right etc., these pecks would produce sequences R-L, L-R, R-R, etc. Each peck was thus counted twice, being recorded as the second peck of one sequence and the first peck of the following sequence. Means, medians, standard deviations, and ranges were calculated for these data for the last five sessions of each condition. We chose medians for most of the figures that follow, but the mean data would show virtually identical results. (Correlation coefficients comparing medians and means were above .99 for all four subjects.) Standard deviations averaged .02 for the different measures across all conditions with 84% of the standard deviations ranging between .01 and .03.

Many of the figures present the data in terms of relative measures: relative response rates, relative sequence proportions, and relative reinforcement rates. Accordingly the table in the Appendix provides corresponding absolute measures by giving the numbers for each of the four sequences, the numbers of reinforcers for each sequence, and the pecks to each key. The table provides information not contained in the Figures. First, since reinforcers were scheduled intermittently, the numbers of sequences (and key pecks) emitted for each reinforcer were relatively large (e.g., around 40 to 45 sequences per reinforcer in Phase I); the table provides the relevant numbers. Second, the figures combine data for all sequences, both those that were reinforced and those that were not. Our inspection of the data indicated that the outcomes were similar whether reinforced sequences were included or not included in the presentation. The interested reader can separate the two classes of sequences simply by subtracting the number of reinforcers for a sequence from the total number for that sequence. Third, most researchers distinguish scheduled and obtained relative reinforcement rates (e.g., 75% of the reinforcers might be scheduled for a response, but in actuality the pigeon might obtain 78% of the reinforcers for that response). Our figures plot behavior as a function of obtained reinforcers. The table shows that scheduled and obtained relative reinforcement rates were quite similar (Stubbs & Pliskoff, 1969).

Phase I. Figure 1 provides data for the individual key pecks, showing the relative number of left-key pecks as a function of relative rein-

forcement rate. Relative reinforcement rates are presented with left-left and left-right sequences combined. The data are presented this way to take into consideration the major manipulation of Phase I, changes in reinforcement for the first response of a sequence (see Table 1). Relatively more left-key pecks were emitted as relative reinforcement rates increased. Relative response rates increased from approximately .35 to .65 as relative reinforcement rates increased from .10 to .90. The change in performance was quite consistent for all four pigeons and occurred in spite of the fact that the key peck that actually produced food was equally probable on the right and on the left. The dashed line at .50 represents matching of the second peck of a sequence to reinforcement proportion for those pecks. The dashed line is at .50 since left and right key pecks produced food equally. The points should fall along this line if the important relation were between those key pecks actually producing food and the proportion of food obtained for those key pecks. The ob-
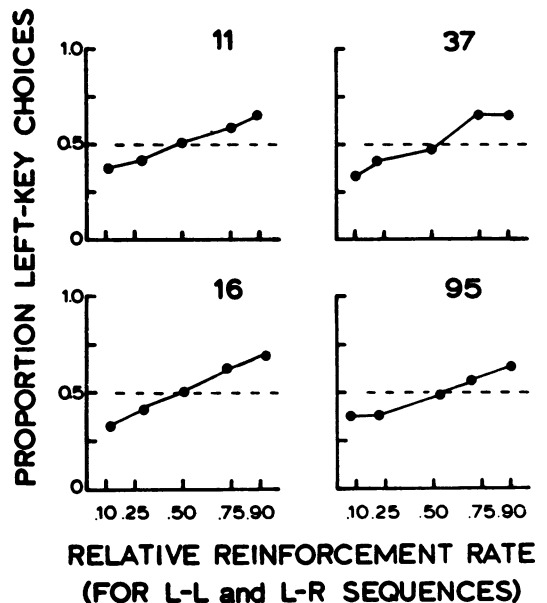

Fig. 1. Proportion of left-key pecks as a function of relative reinforcement rate. Relative reinforcement rates were calculated with respect to the first left of a sequence, giving the combined reinforcers for left-left and left-right sequences (see Table 1). Since left and right key pecks produced food equally, the dashed line represents the (constant) relative reinforcement rate for the pecks actually producing food. Each point is the median of the last five sessions of a condition.

tained deviations from this line demonstrate that more than the last key peck of a sequence was important.

Figure 2 provides a different view of performance by plotting the relative proportion of the different response sequences for the same conditions given in Figure 1. Data are presented for left-left sequences (unfilled triangles), right-right sequences (filled triangles), and the two alternation sequences, left-right and right-left, combined (circles). The alternation sequences were combined since the two are interdependent: the animals could not engage in just one alternation sequence; a change from left to right had to be followed by right to left before a second left-right alternation could take place. As a result of this interdependence, the numbers for the two sequences were equal each session or differed by only one. As in Figure 1, relative reinforcement rates are shown with respect to left-left and left-right sequences combined, to reflect the major change across conditions.

Left-left and right-right sequences changed in orderly ways as relative reinforcement rate changed. The proportion of left-left sequences increased with increases in relative reinforce-

ment rates for sequences beginning with a left response while the proportion of right-right sequences decreased. The relative frequency of alternation sequences remained roughly constant across conditions. Although the proportion of alternation sequences could vary in relation to the remaining sequences, the number of these sequences remained approximately constant across conditions.

The straight lines drawn in Figure 2 represent relative reinforcement rates for the different sequences across changing reinforcement conditions. Table 1 showed that the proportion of reinforcers increased from .05 to .45 for left-left sequences, while they decreased from .45 to .05 for right-right sequences. The reinforcement proportions for the two alternation sequences were averaged together since these two sequences were interdependent. Although the two alternation sequences were differentially reinforced, the two sequences necessarily occurred equally, and so the emission of each sequence was influenced by the reinforcement conditions for both. When, for example, left-right sequences were reinforced with the proportion .45, an increased tendency to emit this sequence would be counteracted by the interdependent decreased tendency to emit a right-left sequence, which was reinforced with a proportion of only .05. The averaging of the two alternation sequences produces the horizontal line at .25.

The data points fall along the straight lines indicating a matching relation between sequence proportion and relative reinforcement for the different sequences. That is, the relative output of a sequence tended to equal or match the relative reinforcement rate for that sequence. Straight lines were fit to the different sets of points using the least-squares method. Figure 2 and the straight-line calculations indicate a slight deviation from matching for left-left and right-right sequences in the direction of undermatching (Baum, 1974). A matching relation was observed between relative sequence output and relative reinforcement rate for alternation sequences. The observed behavior corresponds to predictions based on the averaging of the two alternation sequences: first, that the proportion of alternations should remain constant across conditions, and second that the proportion for each alternation should be .25.
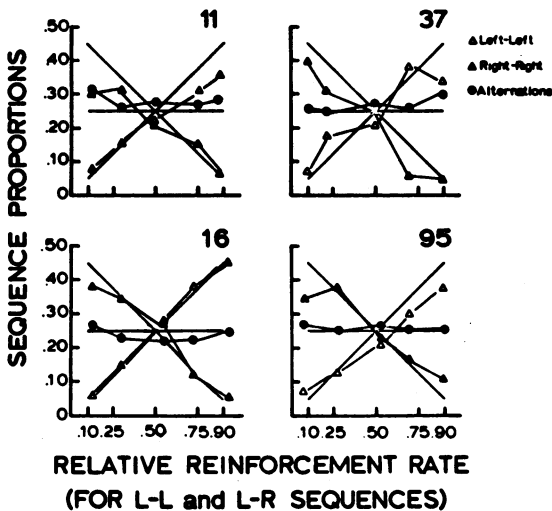

Fig. 2. Sequence proportions for the different sequences as functions of relative reinforcement rate. Relative reinforcement rates were calculated with respect to the first left of a sequence, the combined relative reinforcement rates for left-left and left-right sequences (see Table 1). The straight lines represent matching functions between sequence proportion and the relative reinforcement rate for that sequence. Each point is the median of the last five sessions of a condition.
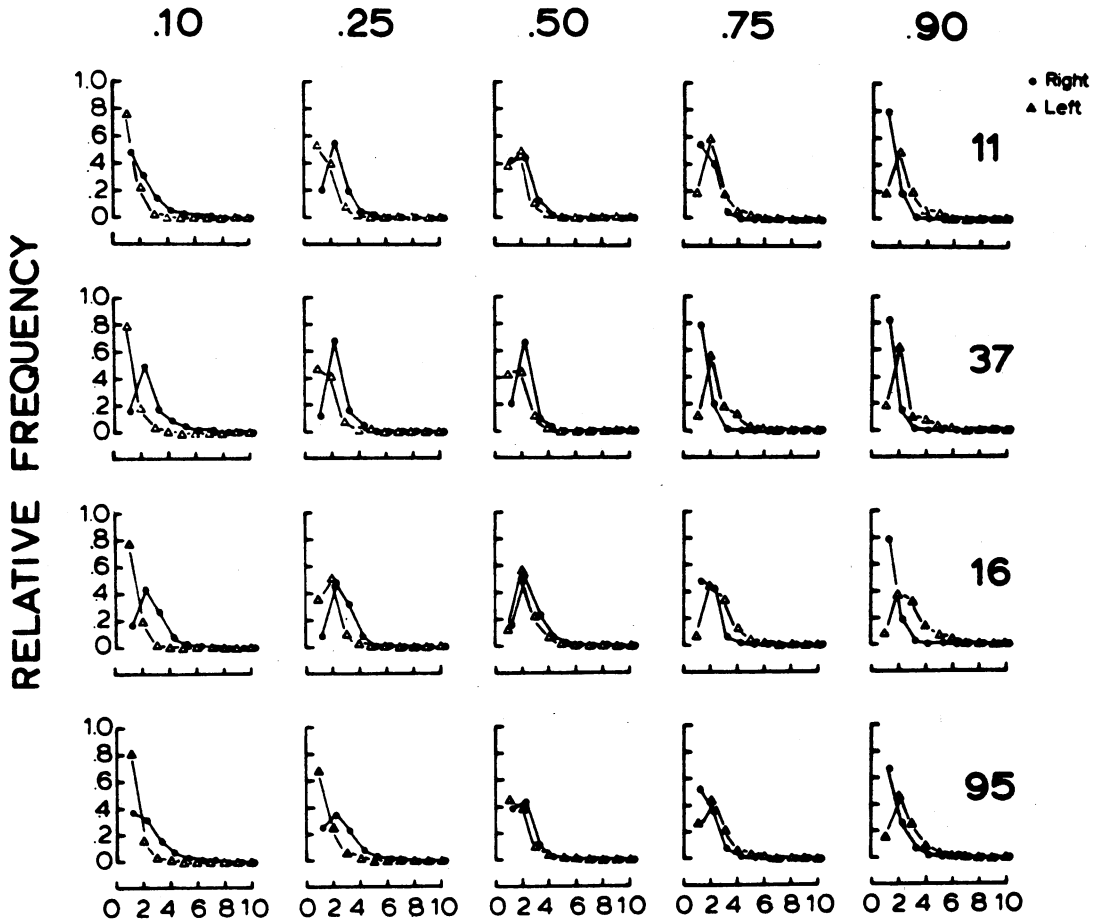
Fig. 3. Relative frequency of pecking the left key (unfilled triangles) or the right (filled circles) successively (run length) from one to ten times. From left to right, the functions are plotted with respect to increasing relative reinforcement rate for the first left of a sequence. Points represent calculations using data summed over the last five sessions of each condition.

Figure 3 provides a more detailed analysis of sequences by giving the relative frequency of different numbers of successive choices to each key. The figure gives the number of times a pigeon pecked once, twice, three times, etc. on a key before switching to the other key. The data were obtained by separately adding the number of runs of each length for the last five sessions of each condition; these numbers were then each divided by the total of all of them to obtain the relative frequencies.

Figure 3 shows that run length increased to the left key and decreased to the right key when relative reinforcement rate increased (for left-left and left-right sequences). As relative reinforcement rate increased, the relative fre-

quency distributions for left-key pecks shifted to the right, indicating a greater number of successive choices to the left key; the distributions for right-key pecks shifted to the left indicating fewer successive choices. All four pigeons tended to peck on a key just once when relative reinforcement rate was low, but peck a greater number of times in succession as the number of reinforcers increased. With relative reinforcement rate at .10, for example, Pigeon 11 pecked only once on the left key in 76% of the instances. When, however, relative reinforcement rate was .90, this bird pecked once in only 21% of the instances. In the remaining instances the pigeon emitted two or more pecks in succession.

An equally striking finding in Figure 3 is that the number of successive choices to a key generally ranged between one and three across all conditions. Run lengths of four or more responses were relatively rare. Run lengths of one or two were obtained in about 80% of the cases and runs of one, two, or three responses in about 95% of the cases. These results indicate the number of successive choices to a key always remained small in spite of large changes in reinforcement conditions. The results show that the pigeons simply alternated between the four two-peck sequences rather than engaging in a long series of responses to either key. At first these results might appear somewhat surprising. With the .90 condition, for example, a series of left-left-left-left-left-etc. provides multiple instances of left-left sequences, sequences that were reinforced relatively often; however the sequence, left-right, was reinforced equally often, so the combination of reinforcement for both sequences would act against long series of left-key responses in favor of a higher rate of alternation (e.g., a pattern such as left, left, right, left, left, right, etc.).

Intertrial interval was varied in the second part of Phase I. Figures 4, 5, and 6 provide the results. Figure 4 gives relative response rates for left-key pecks as a function of intertrial interval. The points approached .50 as intertrial interval was lengthened. The results indicate that the effect of differentially reinforcing left-key responses as the first response of a sequence was attenuated when the intertrial interval was increased. With .5-sec and 1-sec blackouts, the effects of differential reinforcement are clear since more left than right responses were emitted by all birds; with longer blackouts, however, relative response rates were sometimes above and sometimes below .50.

Figure 5 shows the relative frequencies of occurrence for the four sequences. Consider first Pigeon 37. There are two main findings. First, the proportion of left-left sequences declined as a function of intertrial interval, the proportion of right-right sequences increased, and proportion of alternations remained roughly constant. Second, with a short intertrial interval, the ordinal arrangement is what would be expected with 75% of the reinforcers for left-left and left-right sequences combined: left-left sequences occurred most often, alternations with intermediate frequency, and right-right sequences least often. Sequence proportions converged to similar values when the blackout duration was increased. These same findings occurred in a general way for the other pigeons but not to the same degree; and, the data for the other pigeons show exceptions. For example, Pigeon 11 showed similar results to Pigeon 37 but to a lesser degree. The effects
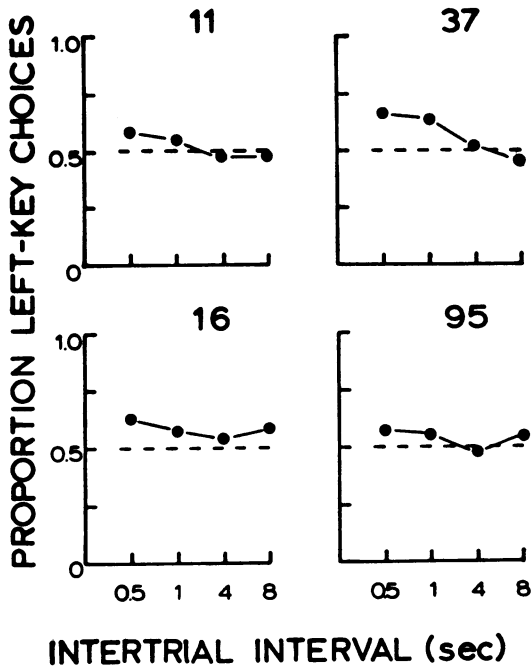

Fig. 4. Proportion of left-key pecks as a function of intertrial interval. Each point is the median of the last five sessions of a condition.
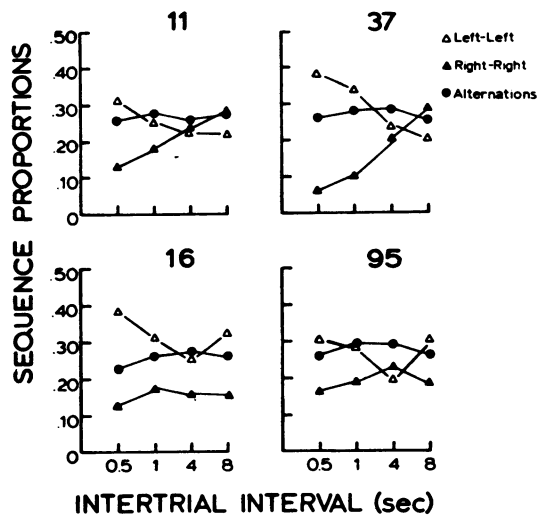

Fig. 5. Sequence proportions as a function of intertrial interval. Each point is the median of the last five sessions of a condition.
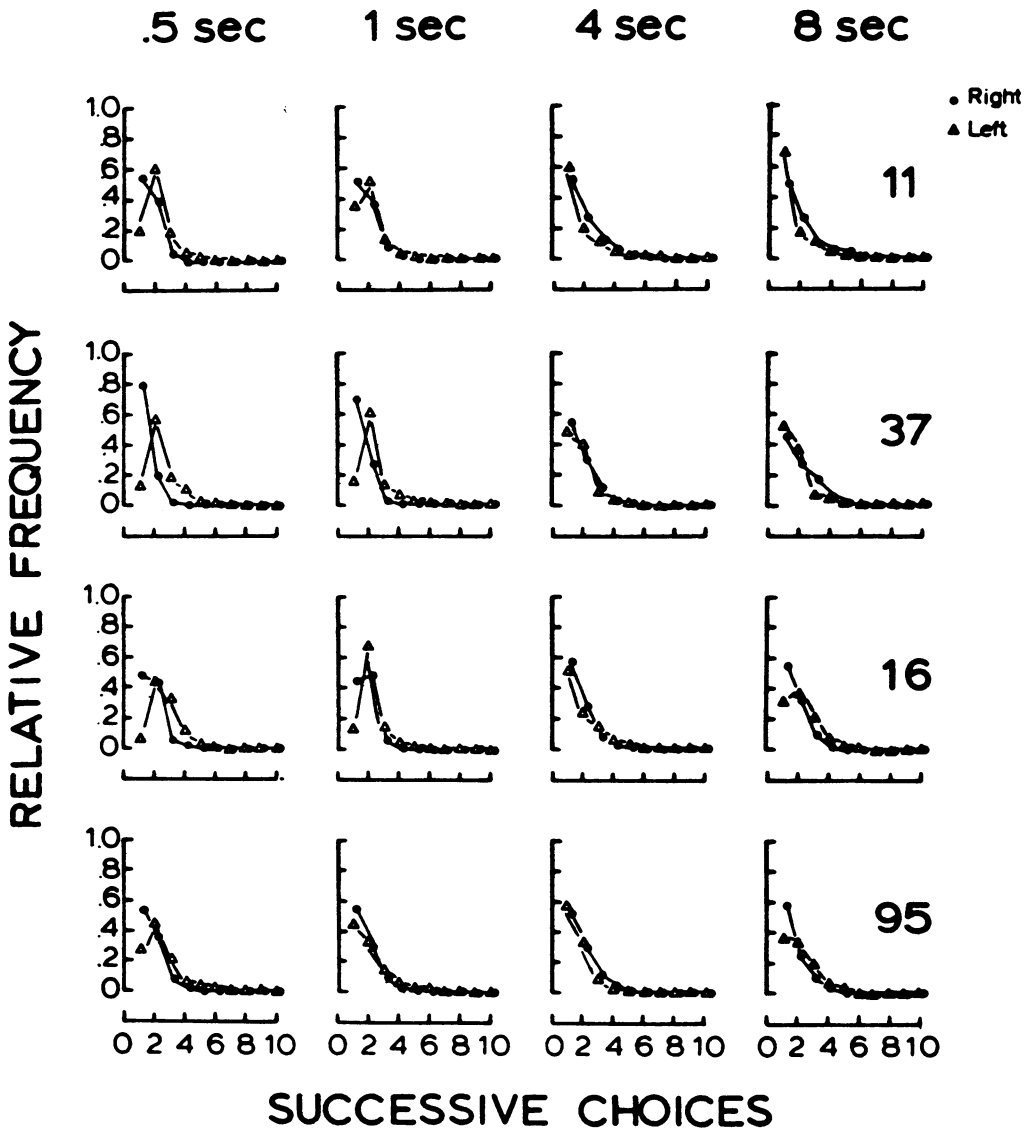
Fig. 6. Relative frequency of pecking the left key (unfilled triangles) or the right key (filled circles) successively (run length) from one to ten times. From left to right, the functions are plotted with respect to increasing intertrial interval. Points represent calculations using data summed over the last five sessions of each condition.

hold less obviously for Pigeons 16 and 95, and show exceptions, especially when the 8-sec intertrial interval was used.

Figure 6 shows relative frequency data for successive choices of different numbers as intertrial interval was increased. With short intertrial intervals, the average number of responses was greater for the left key than for the right, in accord with the previous results (Figure 3). As intertrial interval increased, the most striking change was a shift in the number of left-key responses such that fewer left-key responses

were emitted in succession. For example, the relative frequency of an alternation (a successive choice length of one before switching) averaged .16 for the four birds when the blackout was .5 sec but increased to .46 when the blackout was 8 sec. This change corresponds to an increased tendency for the pigeons to alternate when the intertrial interval was increased.

Phase II. Relative reinforcement rates were varied separately for those sequences that involved alternations and for those that did not. Neither left-key nor right-key responses were

differentially reinforced in this phase, either as the first or the second response of a sequence (see Table 1). Accordingly, we expected equal relative response rates for pecks to the left and right, and in fact relative response rates were close to .50 in all conditions (average absolute deviation from .50 was .02).

Figure 7 gives the proportions of different sequences when relative reinforcement rate was varied for alternation sequences. Separate sets of points are given for left-left and right-right sequences, but only one set for alternations since the two were interdependent. Points for the .50 condition are the same as those shown in Phase I and are presented again simply for comparison. Alternations increased when relative reinforcement rate increased, whereas the two nonalternation sequences decreased. The straight lines in Figure 7 are matching lines that represent cases in which relative frequency of a sequence matched the relative reinforcement rate for that sequence. The points lie near the lines in all cases except one (for Pigeon 37 under the .90 condition), so a matching relation provides a reasonable description of the data. Lines were fit through the points by the least-squares method. Figure 7 and the straight-line data indicate a tendency toward undermatching.

Figure 8 shows data for successive choices to the same key. As was the case in Phase 1, the pigeons generally emitted one, two, or three responses on a key and then changed over across all conditions. Figure 8 shows that there were changes across conditions: the number of successive responses to a key decreased when alternation sequences were reinforced relatively more often. Figure 8 shows that the relative frequency of responses in Class 1 increased across conditions. A successive choice of only one indicates alternation. The results reflect those of Figure 7 that alternations increased in frequency.

Intertrial interval was changed in the second part of Phase II, while relative reinforcement rate was constant at .75. Pigeon 95 died and so only three pigeons were exposed to these conditions. Figure 9 shows the effects of intertrial interval on the relative frequency of the different sequences. There were no major changes in sequence proportions over the range of intertrial intervals used. There was, perhaps, a slight tendency for the different sequences to converge for Pigeons 11 and 37,
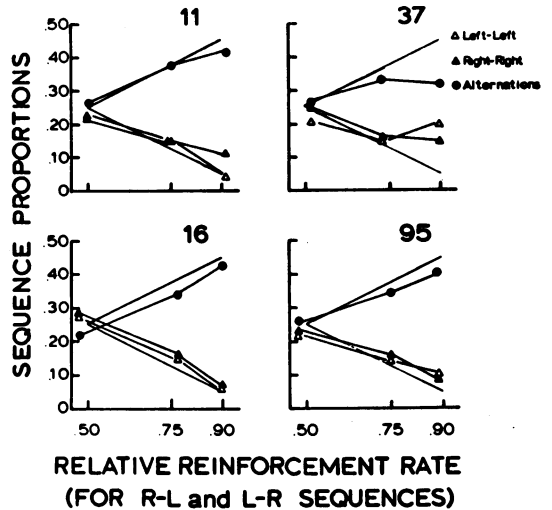

Fig. 7. Relative frequencies of occurrence for the different sequences as a function of relative reinforcement rate. Relative reinforcement rates were calculated with respect to sequences involving alternations, the combined relative reinforcement rates for left-right and right-left sequences. The straight lines are matching functions between sequence proportion and relative reinforcement rate. Each point is the median of the last five sessions of a condition.

but the proportion of alternations remained above those for nonalternation sequences in all conditions. Thus, intertrial interval produced only minor changes in performance on these conditions.

When intertrial interval was changed the data on successive choices were very similar to the data of Figure 8; there were no systematic changes in the relative frequency distributions when intertrial interval was changed.

DISCUSSION

The results remind us of the quote from *Alice's Adventures in Wonderland* following the caucus race: "Everybody has won, and all must have prizes." It certainly seems that the results have something for everyone. The molecular position is supported by the findings that sequences rather than key pecks acted as the functional units and by the findings on the patterns of choice. At the same time, the results support the molar position by demonstrating matching of sequences and even extend matching to a more complex situation. But before we decide whether all have really won, we need to consider these positions in more detail. The labels 'molar' and 'molecular' imply two positions on a single issue, but there really are
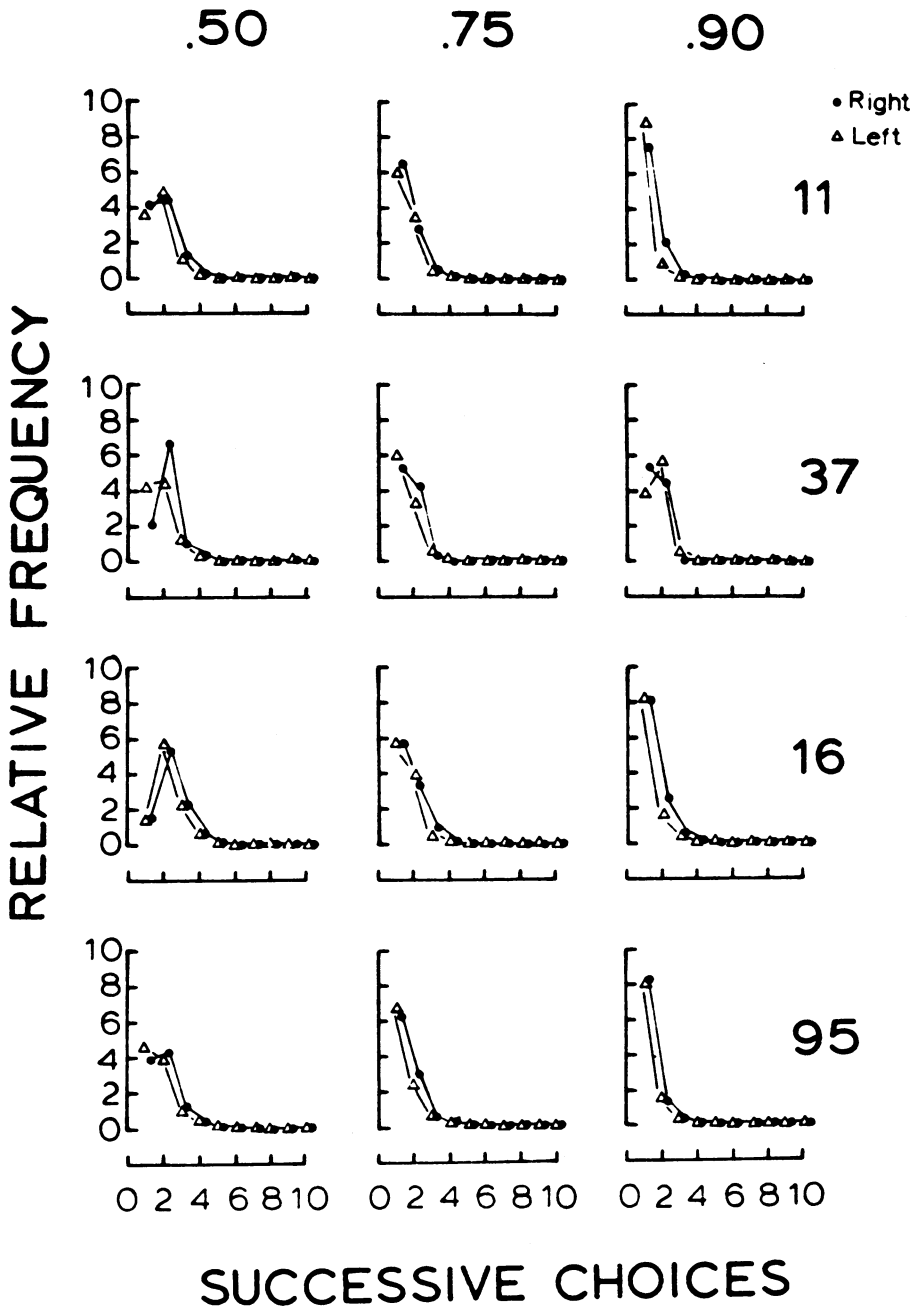
Fig. 8. Relative frequency of pecking the left key (unfilled triangles) or the right (filled circles) from one to ten times in succession (run length). From left to right, the functions are presented when relative reinforcement rate increased for alternations. Calculations were made using data summed across the last five sessions of each condition.

several issues. These issues include the units of behavior, the appropriate measures to use and relations to study, and the specific issue of matching vs. maximizing. These issues are so interrelated that they are typically combined and subsumed under the two labels or positions, but it may be wise to consider them separately.

Units

Stated simply, the issue is whether to consider individual responses or sequences of these

Fig. 9. Sequence proportions as a function of intertrial interval. Each point is the median of the last five sessions of a condition.

responses as the basic units. In typical concurrent situations, reinforcers are arranged for key pecks, and then the experimenter attempts to decide whether the behavioral units really are key pecks or sequences of pecks. Our situation differed by providing explicit reinforcement of response sequences. In one sense the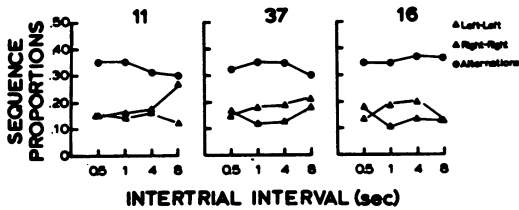 experiment pitted one type of unit against the other by pitting reinforcement of pecks against reinforcement of sequences (Phase I). Simple matching predicts that left and right pecks should occur equally, and this type of matching relation would provide evidence that the key pecks were the functional units of behavior. However, Figure 1 showed a deviation from matching of pecks. Instead, there was matching between sequences and reinforcement, indicating that sequences rather than individual key pecks acted as the functional units. Given this relation, deviation from matching for individual key pecks is a necessary outcome.

The formation of sequences as units depended on the duration of the intertrial interval. Although sequence output differed from pigeon to pigeon in Phase I, it is clear that sequence output did not match relative reinforcement rate when long intertrial intervals were used (Figure 5). Had we picked one of these values rather than the .5-sec duration we chose, matching would not have resulted. Additionally, when the duration of intertrial blackout was increased, the pigeons responded equally on the two keys, in accordance with the equal reinforcement of left and right pecks. These results agree with the results of an experiment (described above) by Silberberg and Williams (1974). The results of both experiments indicate that there are temporal limitations affecting the formation of functional sequences of responses. Inherent in the notion of a sequence is the possibility that the second

response of a sequence is under the control of the first. Control of behavior by prior behavior suggests memory, and factors that presumably affect memory would affect control by a prior response. Duration of the intertrial interval is one factor and both sets of results are consistent with a memory concept (see Silberberg & Williams, 1974, as well as Silberberg et al., 1978, for more detailed discussions).

Discussions of alternative definitions of units typically treat them as mutually exclusive, but it is likely that the units differ from situation to situation, with several factors determining whether pecks or sequences become the relevant units in any given situation. One set of factors is related to the dependency-contingency distinction (Reynolds, 1968). Standard concurrent schedules arrange dependencies at the level of the individual response but also provide contingencies for sequences of these responses. In contrast, our procedure arranged dependencies at the level of two pecks but also provided contingencies for sequences of more than two pecks. What are the effects of arranging the dependencies at different levels? The various results prompt the generalization that the most orderly relations between behavior and reinforcement result at the level of the dependencies; relations at the levels of the contingencies are less orderly and less obvious. Under simple concurrent schedules, matching is typically obtained, and the results suggest that in those situations, individual responses are the functional units. Contingencies are arranged for sequences, but here the picture is less clear. Some have found evidence that sequences may be units in these situations (e.g., Shimp, 1966, 1969; Silberberg et al., 1978); others, however, have not (e.g., Nevin, 1969, 1979; Heyman, 1979). The question of whether sequences act as units is both complex and controversial [see for example, the discussions of the paper by Nevin (1969), in Silberberg et al., 1978; Nevin, 1979 and in press; Shimp, in press; Silberberg & Ziriax, in press]. When two-peck sequences are reinforced, sequences are the units, and these effects override effects at the level of individual pecks (present experiment; Shimp, 1981; Silberberg & Williams, 1974). For the present experiment, we examined event records to record sequences of three and four pecks. There was a relationship between output of these larger sequences and

reinforcement of the sequences, but the relationship was not nearly so strong as those at the level of two pecks.

Perhaps we should not be surprised that different units arise when different procedures are used. Consider the case of reading, which one may do by responding to letters, words, or groups of words. Practiced readers might normally use one unit, groups of words, when reading a novel, but if these readers are given a proofreading task they would shift to different, smaller units. Similarly it seems that animals develop different units depending on the task requirements.

A second set of factors that would influence the development of units would be those factors that could be termed structural. Included would be the time between responses and the complexity of the sequence. Intertrial interval was varied here and in other experiments and does affect sequence output. Regarding sequence complexity, there is not much research, but the best guess is that there are limits on the number of responses in a sequence and on the number of sequences that can be used (e.g., see Schwartz, 1980). Structural factors have been discussed in more detail elsewhere and need no further discussion here (e.g., Shimp, 1978, 1979).

Measurement

Molar and molecular analyses often use different measures and focus on different relationships. Molar analyses of choice emphasize key pecks (or time spent responding), concentrate on two classes of behavior (i.e., left and right responses), use relative frequency measures, and focus on the relation of behavior and reinforcement, generally through the matching relation. Molecular analyses, in contrast, emphasize particular groups of responses, use conditional probability measures for many sequences, and emphasize the relation of behavior to prior behavior; often the pattern of choices is compared to theoretical maximizing sequences. The present analysis falls somewhere between the two. We used relative frequency measures and emphasized the relation of relative behavior output to relative reinforcement rate, which is in keeping with a molar analysis. However, we used four classes of behavior rather than two and, more impor-

tantly, we focused on sequences, in keeping with a molecular analysis.

What are the essential differences between these measures and relations? One that has been proposed concerns the averaging of data. The typical molar analysis of concurrent schedules involving two response topographies segments behavior into two classes and relates them to reinforcement. An implication is that the appropriate relation is one that can be measured only over a long time span. Many have argued that this averaging of data might obscure moment-to-moment response patterns and, as a result, molecular analyses have included more detailed measures of these local changes in responding. Although the different analyses focus on different types of behavior, in one sense they are similar in that they average data over large periods of time. The essential difference lies not with the averaging of behavior but rather with the degree of detail that is necessary. Orderliness may appear at different levels, leading us to ask whether the data at one level are more significant than at another (see also Nevin, in press, for a similar discussion).

A second difference concerns the use of conditional probability measures that describe sequential relations. These measures provide data that cannot be obtained when behavior is divided only into two classes. Conditional probabilities can however be related to frequency data based upon sequences since there is a necessary correspondence between the two sets of data. Thus $P(L/L)$ and $P(L/R)$ have their equivalents in the relative frequency measures, LL and LR, RL and RR. The two sets of measures make similar points, but the conditional probability data emphasize the relation of behavior to prior behavior, whereas the relative frequency data emphasize the entire sequence as it occurs relative to other sequences.

The crucial difference may not be one of measurement, but instead one of the relations that are emphasized. Molar analyses emphasize the relation of behavior and reinforcement. The sequence experiment used larger, structural units but kept this same emphasis. In contrast, the molecular approach, by focusing on conditional probabilities, emphasizes the relation of behavior to prior behavior. Perhaps these different relations should not be placed

in opposition for instead they might focus on different aspects of choice. Emphasis on the relation of behavior and reinforcement, which usually takes the form of the matching relation, simply shows how choice varies as a function of reinforcement. In this sense, the matching relation is only descriptive, not explanatory. Matching remains descriptive until it is placed within the context of a theoretical position, and within such a context matching serves to support other data that provide an explanation of behavior. (See for example how data on matching are used to support Herrnstein's 1970 view of the law of effect.) Emphasis on the relation of behavior to prior behavior could be construed as purely descriptive, but it has been used to support an explanation of choice, as when sequence effects are interpreted in terms of maximizing. But, what is often not clear in these relations is how these patterns relate to reinforcement. Reinforcement is not ignored in these accounts; often response patterns have been compared to theoretical maximizing sequences. However, in most instances where long tables of conditional probability data are given, data are not presented to tell how often these sequences are reinforced.

Matching vs. Maximizing

Data about matching and about sequences can be used in a descriptive way simply to characterize choice. However, these findings are often treated in a more theoretical fashion that raises the issue of the basic processes underlying choice. The issue is whether matching reflects a basic process or whether matching is the byproduct of a more basic, maximizing process. This issue has resisted resolution within the framework of standard concurrent procedures, with good arguments favoring either position. The present results do not resolve the issue, but somewhat favor the matching position. The present findings are consistent with previous research on matching and extend the matching relation to a more complex situation. Matching has been obtained previously when complex behaviors have been used (i.e., concurrent reinforcement involving different interresponse times, Shimp, 1970; Shimp & Hawkes, 1974; Staddon, 1968). What the present results add is the specific use of response sequences; previously, observations of sequences have been taken as evidence for maximizing, but

here the results indicated that sequence output reflected matching.[1]

When we designed the experiment, we expected some relation between sequences and reinforcers. What was unexpected was that the obtained relation would approximate matching so closely. The use of complex units that extended over time, the pitting of reinforcement of sequences against reinforcement of pecks, and the embedding of the sequences in a series of pecks all made the experiment very much different from the usual ones. So, the findings give added weight to views favoring a matching process.

Matching resulted, but what about maximizing? This possibility cannot be ruled out, but it is difficult to determine whether the matching relation was a byproduct of some maximizing process. Three points are relevant. First, observation of sequences suggests a maximizing process in standard concurrent situations when the decision is between pecks and sequences of pecks. In the present experiment, however, sequences rather than individual pecks were reinforced, and as a result, observations of sequences do not provide the same type of evidence for maximizing. It is not clear whether the two-peck sequences were byproducts of larger, possibly maximizing sequences, or whether these larger sequences were a byproduct of the matching-related output of two peck sequences. Second, the analysis of some event records showed that some three-peck and four-peck sequences occurred more than others, and that sequence output was related to reinforcement of these larger sequences. This relation was, however, not as close to the matching relation observed at the level of two pecks, the level at which the dependencies were arranged and the most orderly relation was obtained. It would seem therefore that two-peck sequences were the basic units. The occurrence of three-peck and four-peck sequences might have resulted in part from the emission of the two-peck units with different frequencies. Third, if matching were a byproduct of some

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[1]Reinforcers were arranged according to the interdependent procedure of Stubbs and Pliskoff (1969). This procedure ensures that relative reinforcement rates are fixed and that the units selected for reinforcement must be emitted. The procedure forces responding to some degree, but it does not force matching. A worthwhile experiment might involve use of independent scheduling of reinforcers to see if similar results obtain.

more molecular maximizing process, it would seem that there should be a maximizing sequence of sequences. Such sequences have been observed with simpler procedures (e.g., Shimp, 1966), but it is difficult to say what the optimal sequence of sequences would be. The relative frequency data of Phase I (Figure 3), as well as event records, revealed a tendency toward a response pattern, LLRLLR etc., when sequences LL and LR were reinforced relatively often. At first glance this pattern might suggest maximizing since the embedded sequences, LL and LR, were the ones most often reinforced. However, the pattern, LLRLLR etc., is not enough; this pattern produces equal frequencies for the sequences LL, LR, and RL but includes no instance of RR. The matching relation does not result from this pattern; additional LL sequences and some RR sequences would have to be emitted. And, these sequences would have to occur in precise numbers for matching to result. The results then provide little support for a maximizing process. The intent, however, is not to argue that maximizing did not occur; rather, to point out that it is very difficult to say that maximizing did occur.

The prizes then are not for molar and molecular positions but rather for specific points raised by researchers on both sides. Our results suggest that the current emphasis on molar and molecular positions as antagonistic should be replaced by one that is more complementary and seeks to integrate the different analyses into a broader view of choice (cf. Catania, 1979; Nevin, in press). The present data may represent one step toward such an integration. Our results do not favor one position over the other; instead, the more striking feature of the results is the compatibility with much that has been termed molar and molecular. The present results are encouraging and represent only a beginning. There are other promising possibilities: use of more complex sequences or different ways of arranging sequences come quickly to mind. Part of the reason for the many conflicting views of choice might be that most of the research has used simple concurrent schedules and probability matching procedures. Perhaps these situations do not permit a clear decision between alternative views; use of different procedures may help in this regard. Just as research with second-order schedules has clarified our knowledge of be-havioral units (e.g., Gollub, 1977), research with concurrent reinforcement of sequences may clarify our understanding of choice.

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APPENDIX

Table A

Numbers of occurrences of the four sequences, of reinforcers for the four sequences, and of pecks to the two keys. The numbers are means of the last five sessions of each condition.

BIRD 11

	SEQUENCES					*REINFORCERS*					*PECKS*	
Condition	*L-L*	*L-R*	*R-L*	*R-R*		*L-L*	*L-R*	*R-L*	*R-R*		*Left*	*Right*
					Phase I							
6	132	508	508	440		4	3	28	25		640	948
7	292	516	516	579		9	9	19	22		809	1095
8	387	489	489	364		14	16	14	16		876	853
3	576	510	510	258		22	23	8	7		1086	769
2	532	431	431	96		28	25	2	4		964	527
1	364	411	411	258		21	26	7	6		775	668
4	138	175	175	163		23	22	7	8		313	338
5	95	161	161	178		23	23	6	8		257	339
					Phase II							
9	65	580	579	163		2	27	28	2		645	742
10	280	611	611	204		7	23	23	7		891	815
11	166	442	443	206		7	23	21	8		609	649
12	119	204	203	139		8	22	22	7		322	343
13	64	152	152	137		9	23	21	8		215	289

BIRD 37

	SEQUENCES					*REINFORCERS*					*PECKS*	
Condition	*L-L*	*L-R*	*R-L*	*R-R*		*L-L*	*L-R*	*R-L*	*R-R*		*Left*	*Right*
					Phase I							
6	148	532	533	794		2	3	27	28		681	1327
7	364	541	540	639		6	7	25	22		904	1180
8	428	562	562	545		13	17	16	14		990	1107
3	853	596	596	140		23	22	9	5		1449	736
2	722	627	627	114		26	29	3	3		1348	741
1	540	438	438	139		24	23	7	6		979	577
4	146	195	195	132		20	22	9	9		341	328
5	112	134	134	137		23	25	5	7		245	272
					Phase II							
9	412	614	614	300		2	30	24	3		1026	914
10	246	515	515	245		7	24	19	10		760	761
11	222	449	449	132		10	21	22	7		670	580
12	158	266	266	98		9	24	17	9		425	364
13	114	173	173	102		9	22	22	8		288	276

BIRD 16

Condition	SEQUENCES					REINFORCERS					PECKS	
	L-L	L-R	R-L	R-R		L-L	L-R	R-L	R-R		Left	Right
					Phase I							
6	158	596	596	840		4	3	21	31		753	1437
7	492	628	628	975		10	8	18	23		1120	1603
8	763	600	600	751		18	15	12	15		1363	1351
3	1039	624	624	353		19	23	6	11		1649	988
2	1145	613	613	145		29	27	2	2		1758	756
1	494	427	427	268		23	23	7	7		921	695
4	186	205	205	123		23	22	10	5		391	329
5	156	131	131	79		22	24	7	7		287	210
					Phase II							
9	191	982	982	197		3	26	28	3		1172	1179
10	273	678	678	394		6	24	23	6		955	1072
11	368	692	692	191		7	21	25	7		1061	883
12	168	309	309	71		9	20	23	7		475	380
13	74	197	197	76		7	23	23	6		270	273

BIRD 95

Condition	SEQUENCES					REINFORCERS					PECKS	
	L-L	L-R	R-L	R-R		L-L	L-R	R-L	R-R		Left	Right
					Phase I							
6	166	647	647	817		2	2	28	27		813	1464
7	307	682	683	1002		6	7	21	25		989	1684
8	606	731	731	624		19	13	14	14		1337	1355
3	670	597	597	368		21	22	10	7		1267	965
2	778	549	549	235		27	27	3	4		1328	784
1	450	491	491	333		22	24	6	7		941	824
4	137	216	216	165		21	24	8	7		353	380
5	160	131	131	94		21	24	9	6		291	227
					Phase II							
9	246	944	944	213		4	26	27	3		1190	1157
10	338	756	757	369		7	23	21	9		1095	1125