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SEQUENCES OF SPACED RESPONSES: BEHAVIORAL UNITS AND THE ROLE OF CONTIGUITY

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Sequences of temporally spaced responses were reinforced to investigate the effects of delay of reinforcement on the formation of functional behavioral units. In Experiment 1, rats' two- and three-response demarcated sequences of left and right lever presses were reinforced such that different response distributions would occur depending on whether the sequences themselves or individual responses were functional units. The matching law could thus be obeyed either by individual responses or by sequences, but not by both; intermediate results were possible. Both regular (nonretractable) and retractable levers were used; the retractable levers precluded the occurrence of insufficiently spaced responses. At a minimum interresponse time of 5 s for regular levers and 7 s for retractable ones, matching results were intermediate, with greater evidence of sequence conditionability in the two-response sequences than in the three-response sequences. In Experiment 2, the required minimum interresponse spacing for two-response retractable-lever sequences was varied in an attempt to locate the sequence matching threshold. This attempt was unsuccessful, but the sequences (instead of individual responses) more closely obeyed the matching law. In the shortest spaced condition, conditional probability data on Lag 1 sequence emission order showed marked, highly similar patterning for all rats, indicating sequential control of the sequences. Post hoc definition of the behavioral unit in these studies is ambiguous. Although reinforcement contiguity was important, aspects of the results could support both molar- and molecular-level interpretations.

Key words: delay of reinforcement, sequences, behavioral units, matching law, molar–molecular question, behavioral patterns, differential-reinforcement-of-low-rate schedules, lever press, rats

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The temporal contiguity between responses and consequences is a powerful variable in operant behavior, and yet, as Lattal (1987) commented, "a systematic experimental analysis of delay of reinforcement . . . has not been forthcoming" (p. 107). By combining aspects of two lines of research related to delay of reinforcement, the present study sought to contribute to such a systematic analysis. This approach entailed an investigation of response sequences as units of behavior.

The nature of functional response units is an issue closely related to the role of contiguity: Sequences of individual lever presses or key pecks, for example, might function as one response, cohering and changing as a unit. The extent to which reinforcement at the end of such a sequence can strengthen the first responses in the sequence may depend partially on sequence length and duration, and hence, on the delay of reinforcement. The issue of whether response sequences are truly operant units is still unsettled (e.g., Zeiler, 1986), in part because the criteria for defining units are ambiguous. As Zeiler (1977, p. 226) pointed out, the mere occurrence of a predictable pattern of behavior does not make a unit: The unit must be shown to be itself conditionable. In addition, occurrences of a sequence unit should be a function of its consequences under a variety of different conditions (but cf. Marr, 1979, pp. 224–225).

Under these criteria, research on the fixed-ratio (FR) schedule pattern has suggested unitary properties (DeCasper & Zeiler, 1974; Kelleher, Fry, & Cook, 1964; Zeiler, 1977). Studies in which sequences are explicitly reinforced as such have carried this line of investigation further. Among those sequence studies that directly address delay-of-reinforcement issues (e.g., Catania, 1971; Catania & Keller, 1981; Neuringer, 1991; Shimp,

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1982), Shimp (1981) reinforced pigeons' emission of the four possible two-response sequences on left (L) and right (R) keys. Blackouts from 1 to 10 s followed each response; reinforcement was provided only after a blackout, and thus was never contiguous with a key peck (because pigeons seldom peck during blackouts). Sequence conditionability was demonstrated, in that sequences with higher obtained reinforcement rates occurred relatively more often. Whether individual sequence response rates occurred in the same proportion as (i.e., matched) corresponding sequence reinforcement rates, however, was not ascertained; the effects of the blackouts are also unclear.

The present project is most closely related to a similar line of research conducted by Stubbs and his colleagues. For example, Fetterman and Stubbs (1982) found not only conditionability but matching using undemarcated two-response sequences. The matching law (see Herrnstein, 1970) has such wide generality that this finding in itself surely militates strongly in favor of viewing the sequences as the functional units of behavior. However, the lack of a stimulus change at the end of each sequence may cloud interpretation of these results; a series of L-R-L-R key pecks must be counted as a series of overlapping LR, RL, and LR sequences. Avoiding this ambiguity, Stubbs, Fetterman, and Dreyfus (1987, Experiment 1) reinforced *demarcated* two-response and three-response sequences for two groups of pigeons. To demarcate the sequences, the final peck in a sequence produced a 1-s timeout, during which the chamber was dark. Reinforcement was delivered through an overall variable-interval (VI) 30-s schedule: After the end of the VI interval, one sequence was set up for reinforcement. The probability of reinforcement for the sequences was manipulated such that matching of sequences was pitted against matching of individual responses: Good sequence matching precluded good individual response matching, and vice versa (see also the method of Shimp, 1981). Under these conditions, the sequences that were reinforced with higher probability occurred more often, lending support to the conclusion that they functioned as discrete units. Further, most sequences obeyed the matching law.

Stubbs et al. (1987) also analyzed the conditional probability of sequence emission order to determine whether that order was random. Although effects were unclear for the three-response sequence group, data for the two-response sequence group showed that sequences were usually not immediately repeated, and had some tendency to be emitted in systematic patterns. This evidence further supported the conclusion that reinforcement had strengthened two- and three-response sequences of pigeons' key pecks as likely units. In the present study, their procedure was modified in order to focus on delay of reinforcement: Two- and three-response sequences of *spaced* responses were reinforced.

For sequences of spaced responses to function as units, reinforcement must strengthen responses that are not closely contiguous with reinforcer delivery. If, however, close contiguity is critical, the sequences would not become units; instead, the matching law would be obeyed at the more molecular level of individual responses, or intermediate results would be produced. Because changeover delays (CODs) of 5 to 10 s have been found necessary for rats on concurrent schedules in order to dissociate the components adequately (see de Villiers, 1977, p. 243, for a list of citations), the current procedures explored this range of spacing.

A reinforcement schedule suitable for generating temporal spacing within sequences is the differential-reinforcement-of-low-rate (DRL) schedule, and a version of it was incorporated in the present research. Rats normally respond fairly efficiently on low-valued DRL schedules (e.g., Schoenfeld & Farmer, 1970, Experiment 3). However, incorrectly spaced responses do occur and potentially interfere with interpretation of the results; thus, the final conditions of Experiment 1, and all those of Experiment 2, were conducted with retractable levers that precluded incorrectly spaced responses.

Use of the DRL contingency has another advantage for research on sequences. Due presumably to the increased effort required for response alternation between operanda, sequences such as RL and LRL have been found to occur less frequently than those sequences without response alternation (e.g., RR; see Morgan, 1974; Page & Neuringer, 1985; Stubbs et al., 1987; Wasserman, Deich, & Cox, 1983; Wasserman, Nelson, & Larew, 1980; but cf. Catania, 1971). The DRL contingency

in the current project may avoid this interference: Organisms sometimes leave the immediate vicinity of the operanda during DRL intervals, resulting in diminished effort to switch operanda.

EXPERIMENT 1

METHOD

Subjects

Eight individually housed, experimentally naive male Sprague-Dawley rats were maintained at about 85% of their free-feeding weights, with water freely available in their home cages. All rats were about 4 months old at the start of the study.

Apparatus

Two standard Lafayette two-lever operant chambers with houselights were used. Fans in the insulating shells provided ventilation and masking noise; windows were covered to make the shells relatively impervious to light.

Food pellets (Bio-Serv 45 mg) were delivered in a food cup centered 2 cm above the floor on the main panel of the chamber. The two levers were located on either side of the food cup at a height of 7 cm and a center-to-center distance of 12.5 cm. A minimum force of 0.16 N was required for a lever-press response to be registered. Responses produced a clicking sound on the regular levers and retraction on the retractable levers. The apparatus was controlled and the data recorded by VIC 20® or Commodore 64® computers.

Procedure

Five training conditions were designed to gradually bring about steady, appropriately spaced responding equally divided between the two levers. Condition 5, immediately preceding the major experimental condition, consisted of a two-lever DRL 5-s schedule in combination with a VI 60-s schedule (range, 1 to 119 s, randomly generated by computer). Rats spent an average of 105 sessions completing training. (Other details concerning the training conditions are available from the first author.)

The 8 rats had been randomly divided into two equal groups at the start of the experiment, but only in Condition 6 were they treated differently. For Rats A through D, two-response sequences of spaced responses were reinforced: left-left (LL), left-right (LR), right-left (RL), and right-right (RR). A correctly emitted LR sequence consisted of an L response after an interresponse time (IRT) of at least 5 s, followed by another IRT of at least 5 s, followed by an R lever press. Whether reinforced or not, correctly executed sequences were demarcated by an immediate 2-s period of the houselight blinking quickly on and off. These 2 s were counted as part of the next spacing requirement, which remained at 5 s. (To ensure that no differential consequences accrued to responses of different duration, responses could not be recorded during these 2-s periods.) The next correctly spaced response after the end-of-sequence demarcation stimulus began the next sequence. Thus, the series of correctly spaced responses (L-R-houselight-blinking-L-R-houselight-blinking) was treated as two LR sequences and not as two LR sequences and one RL sequence.

In the regular-lever subconditions, which will be discussed first, timeout contingencies were used to increase the proportion of correctly spaced responses: A 5-s timeout with the houselight off was produced whenever a time-in IRT of less than 5 s occurred. Responses that occurred during the first 2 s of the timeout period had no consequences, to permit carry-over responding from time in, but each response thereafter extended the timeout by 3 s. The VI timer continued to run during timeout. Timeout responses (i.e., responses that either incurred timeout or occurred during timeout) were never considered to be components of correctly emitted and potentially reinforceable time-in sequences. Instead, the first correctly spaced time-in response after the end of a timeout began the next sequence.

Correctly executed sequences were reinforced if they met two conditions: (a) The last response in the sequence occurred after the VI period elapsed, and (b) that particular sequence had been probabilistically chosen for reinforcement. To allow the determination of matching along a spectrum of sequence emission rates and associated reinforcement rates, different subconditions of Condition 6 were run (see Table 1). Reinforcement probabilities were assigned such that different response allocations would be obtained if the sequences, instead of individual lever presses, were func-

Table 1

Experiment 1, Condition 6: Scheduled sequence relative reinforcement rates.

Group	Lever type and subcondition		
		LL and LR	RL and RR
Two-response	Regular 1	.65 (.325 each)	.35 (.175 each)
	Regular 2	.10 (.05 each)	.90 (.45 each)
	Regular 3	.90 (.45 each)	.10 (.05 each)
	Retractable 4	.35 (.175 each)	.65 (.325 each)
	Retractable 5	.65 (.325 each)	.35 (.175 each)
		LLL, LLR, LRL, LRR	RLL, RLR, RRL, RRR
Three-response	Regular 1	.65 (.1625 each)	.35 (.0875 each)
	Regular 2	.10 (.025 each)	.90 (.225 each)
	Retractable 3	.90 (.255 each)	.10 (.025 each)
	Retractable 4	.65 (.1625 each)	.35 (.0875 each)

tional response units. For example, in the first subcondition for the two-response sequence group, LL and LR sequences together were assigned a relative reinforcement probability of 65% (32.5% each), whereas RL and RR sequences were accordingly only at 35% (17.5% each). If the sequences acted as units, then, more left than right responses would be emitted. The reinforcement proportions for the final responses in the sequences, however, were equally divided between left and right (e.g., for left, 32.5% from LL and 17.5% from RL equals 50%), and this 50/50 split was maintained throughout all subconditions. If response matching predominated, choice proportion would then remain approximately 50/50 throughout Condition 6.

For Rats E through H, similar procedures were followed, but three-response instead of two-response sequences were required. The only procedural difference was an overall VI 50 s (range, 1 to 99 s) instead of VI 60 s; this partly compensated for the greater difficulty in emitting the chosen sequence with eight possibilities instead of four. The eight three-response sequences are given in Table 1, along with the reinforcement probability sets in each of the subconditions. For this group, not only was the last response in a sequence reinforced equally on both left and right levers, but so was the next-to-last. The only reinforcement probability split that was not 50/50 applied to the first response in the sequences. For both groups, both moderately skewed (65%/35%) and extremely skewed (90%/10%) subconditions were included.

Stability criteria were similar for both groups. First, a nine-session basis was used for response rate, such that the largest difference between the three medians of the last three consecutive three-session blocks had to be less than 15% to 20% (two-response) or 20% to 25% (three-response) of the nine-session mean, and no significant trends could be present. Both the left-lever and right-lever response rates had to meet this criterion. Second, a minimum number of 25 (two-response) or 40 (three-response) sessions were required in each subcondition. Third, the averages of each of the individual sequence emission rates for the first 4 of the 9 days had to be similar to the corresponding averages for the last 4 days: within about 0.06 to 0.07 sequence emissions per minute for two-response sequences and 0.03 for three-response sequences. Finally, changeover rate and timeout-response rate were checked for any unusual variability.

As shown in Table 1, two retractable-lever subconditions ended the experiment, the second of which was a replication of the regular-lever Subcondition 1 set of probabilities. These retractable-lever sessions were identical in every possible way to the regular-lever sessions. The force required to depress the retractable levers, for example, was within 0.01 N of that for the regular levers. The only differences in the retractable-lever subconditions stemmed from the retractability: No timeout responses could occur, because both levers were retracted for a fixed duration immediately after a response was made on either lever. Because of the increased emission rate of correctly spaced

sequences, the overall VI 60 s of all the two-response sequence subconditions could be used for the three-response rats as well, instead of VI 50 s. In addition, the previous 2-s houselight blinking after sequence completion was increased to 3 s to offset the noise and salience of retractable-lever withdrawal.

Choosing the minimum IRT for the retractable levers was not straightforward: In the regular-lever subconditions, the actual IRTs in correctly spaced sequences varied from the minimum of 5 s on up. Even if data could have been taken on the demographics of the actual spacing, there would be no clear choice of a "most representative" spacing. Thus, the minimum time between recordable retractable-lever responses was chosen to be an adequately comparable 7 s. Observation showed that rats usually responded on the retractable levers immediately after their extension into the chamber.

To keep the stability criteria for regular- and retractable-lever subconditions comparable, the minimum number of sessions was lowered to 20 (two-response) or 30 (three-response), and the first and last 4-day sequence emission rate comparisons had to be within about 0.09 to 0.10 (two-response) or 0.05 (three-response) sequence emissions per minute. In other respects, the stability criteria were identical. Data recorded in regular- and retractable-lever sessions were also identical, except for timeout-response rate.

In addition, a limited amount of sequence conditional probability data was taken for each rat: The order of occurrence of correctly emitted sequences was recorded by hand. Timeout responses were not included (regular-lever subconditions). One session within the last nine sessions of a two-response sequence subcondition was recorded in this manner and used for data analysis. To compensate for the smaller number of sequences emitted in the three-response sequence subconditions, data from two sessions among the last nine were included. Conditional probability data were taken in two-response sequence Subconditions 2 and 5, and in Subcondition 4 for three-response sequence rats. No data were taken for the three-response sequence rats in regular-lever subconditions because too few correctly spaced sequences were emitted in a session to permit a meaningful analysis.

The number of sessions in each subcondition of Condition 6 is given in Appendix 1; these values do not include sessions in which equipment malfunctions affected more than half of the period. Rat B spent so many sessions completing Subcondition 2 that he was not exposed to Subcondition 3.

Sessions were conducted at the same time each day, 7 days per week. All sessions began with 1 min of timeout with the houselight off, and all Condition 6 sessions lasted 61 min altogether.

Results

The results fall into two categories: matching analyses and conditional probability analyses.

Matching Analyses

Major results. Matching data at the individual response level are presented in Figures 1 and 2. Left response-rate and reinforcement-rate proportions were calculated for each subcondition and the difference between them plotted. The reinforcement-rate proportion was subtracted from that for response rate, so positive differences indicate more L responding than predicted by response matching; a difference of zero indicates perfect matching.

For these response matching graphs, results were averaged over the final 5 days of each subcondition for response and sequence proportions and over the final 6 days for reinforcement proportion. The extra day was included for the latter because results from the training conditions and elsewhere (e.g., Davison & Hunter, 1979) confirm that reinforcement distribution in one session affects responding in the session immediately following. In the regular-lever subconditions, only correctly spaced response rate results were used; the total response rate results, which included timeout responses as well, were not. Because discrimination of time in/timeout was good, correctly spaced responding would be expected to match if individual lever presses were the functional units, whereas total responding might or might not. In fact, the total results were generally very similar to those provided: In almost all cases, differences were within 5%. Absolute measures upon which these proportions are based can be found in Appendix 1.

In most cases, the obtained reinforcement distribution for the final response in the sequences was indeed close to 50/50, as pro-

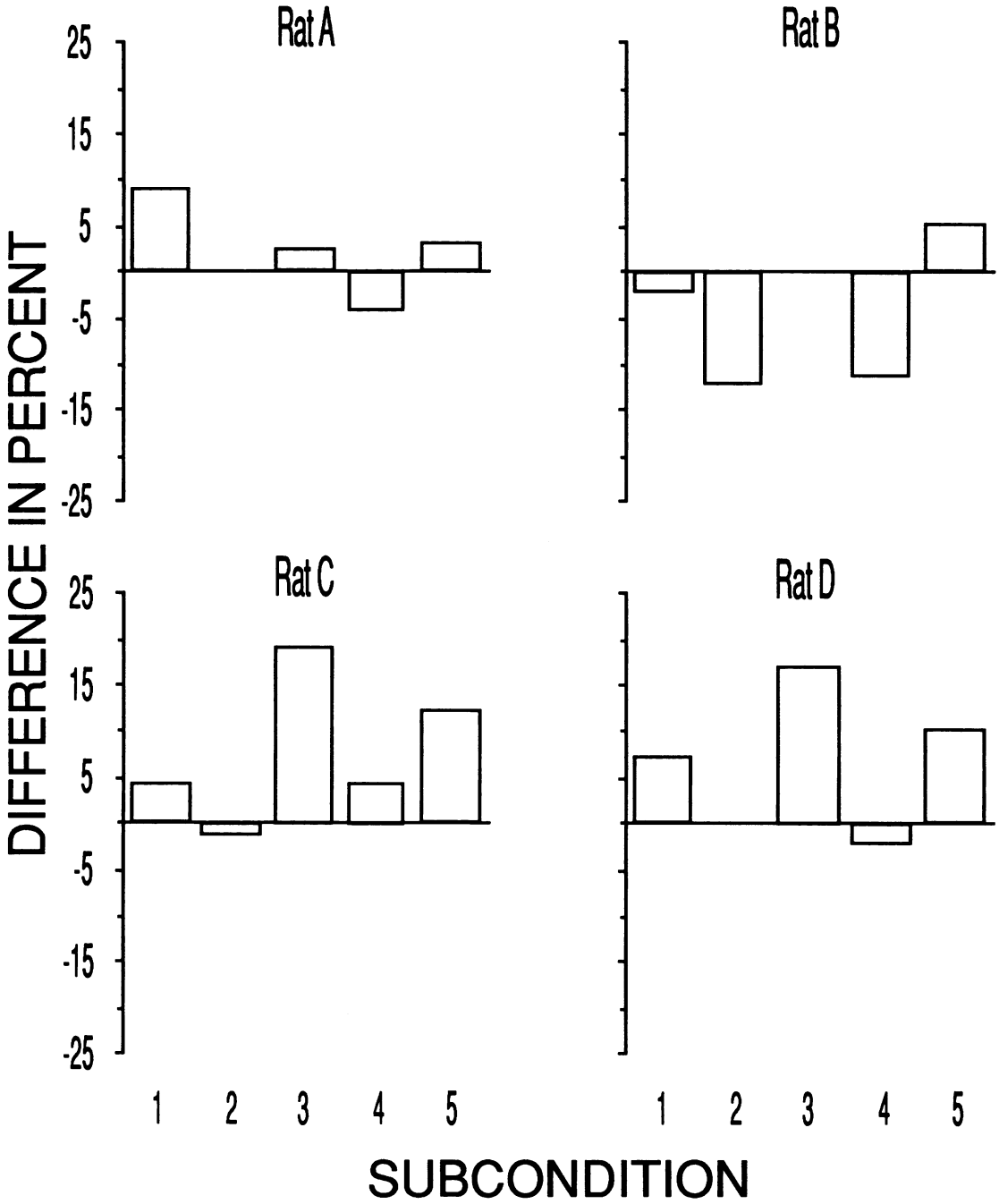

Fig. 1. Response matching graphs showing the difference between L response-rate proportion and L reinforcement-rate proportion in Experiment 1, Condition 6, two-response sequences. Positive differences indicate higher L response rates than predicted by response matching; differences near zero indicate good response matching.

grammed: Over half of the time, the distributions were within 5% in either direction, and in nearly all cases were within 10%. In the outlying cases, the programmed 50/50 split was more closely approached over longer periods of time. Four such instances occurred in the three-response regular-lever sequence subconditions due to low reinforcement rates; the only other case was Rat B, Subcondition 1 (71% L reinforcement-rate proportion). In this

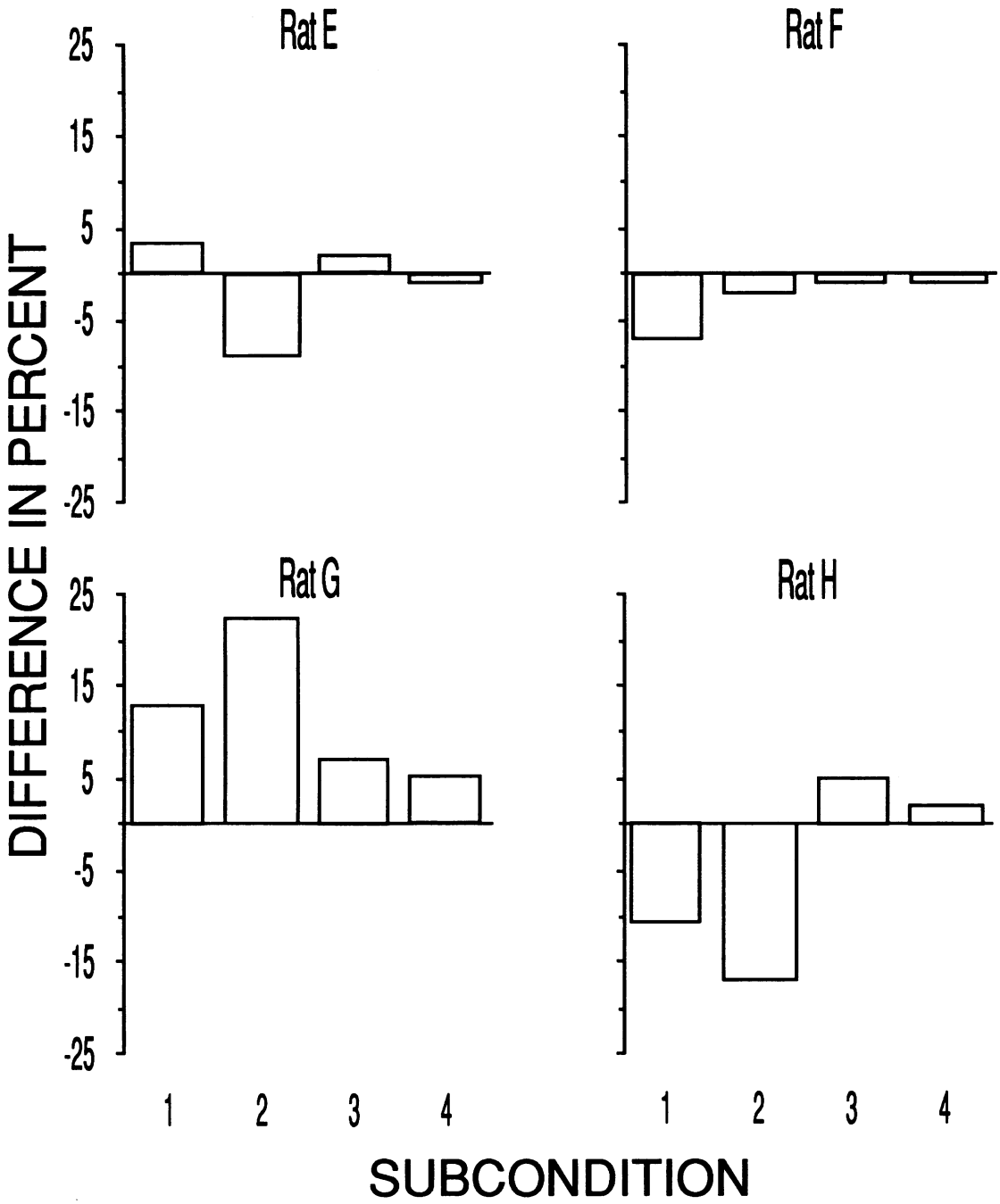

Fig. 2. Response matching graphs showing the difference between L response-rate proportion and L reinforcement-rate proportion in Experiment 1, Condition 6, three-response sequences. Positive differences indicate higher L response rates than predicted by response matching; differences near zero indicate good response matching.

subcondition, both response matching and sequence matching could potentially be obtained simultaneously during the final sessions.

Figure 1 displays the response matching graphs for each two-response sequence subcondition, and Figure 2 presents the three-response sequence results. Many of the differences from perfect matching were less than 5%, suggesting response matching. However, an important additional piece of information

is the lever preference expected if the sequence-level contingencies were influential. The direction of this skew can be determined from Table 1. For the two-response sequence rats, the expected preferred lever alternated for each subcondition, from L to R to L to R to L. Thus, a response matching graph that showed positive differences (more L responding) for Subconditions 1, 3, and 5 and negative ones for Subconditions 2 and 4 could indicate an effect of the sequence-level contingencies even if response matching was present. The three-response sequence rats followed an L-R-L-L sequence. Table 1 also shows that some subconditions had more extreme sequence reinforcement probability splits than others, a factor that would affect the extent of the difference observed if sequences were the functional behavioral units.

Left responding did indeed move in the direction of sequence matching in every subcondition (Figure 1). For Rats B, C, and D, the most extreme differences occurred in Subconditions 2 or 3, where the sequence-level contingencies were most skewed. Quantitatively, if sequence-level matching were occurring, the difference expected for Subconditions 1, 4, and 5 is 7.5%, and for Subconditions 2 and 3, 20%. Simple coincidental lever bias could not explain the patterning observed because bias should not have occurred in the direction of sequence matching more often than in the opposite direction. Further, such lever bias might be expected to persist in the same direction throughout.

Figure 2 shows that the response-matching results for the three-response sequence rats were quite different: For the regular-lever subconditions in particular, no consistent pattern emerged. However, in the retractable-lever subconditions, either response matching was very good or responding was skewed in the direction of sequence matching (i.e., positively). Here, the expected difference given sequence-level matching is 5% for Subconditions 1 and 4 and 13.3% for Subconditions 2 and 3. In contrast to the two-response sequence group, only a few results approach these values.

Graphs were also plotted for a sequence "matching index." This measure was calculated as the percentage difference from perfect sequence matching for each sequence, averaged across all sequences for each session in a subcondition. If the sequence emission rates perfectly matched reinforcement rates, the matching index would be zero for that session; at the other end of the spectrum, the highest possible matching index for two-response sequence rats was 50%. The changes in sequence conditionability over time could thus be graphically represented. The results for Rat B, Subcondition 2 were especially illuminating (Figure 3). The marked trend in Figure 3 demonstrates that Rat B responded to the sequence-level contingencies, and depicts in addition the dynamics of the process. Because the programmed L/R reinforcement distribution for the last response in the sequences was always 50/50, the steady change from a left preference to a right preference demonstrated in this figure could only have occurred in response to the more molar-level contingencies. However, whereas Rat B's performance was sensitive to these sequence-level contingencies, it was a marginal sensitivity that produced a glacial pace of change. This graph, then, exemplifies the intermediate nature of the results of Experiment 1. Other rats' results bracketed these, with some showing faster downward trends to the point of an immediate change and others showing no evidence of sequence conditionability.

Supplementary matching analyses. A more fine-grained analysis produced some minor results that are worth noting. As discussed previously, past research has discovered that sequences with no response alternation (e.g., RR, LLL) tend to be emitted at higher rates, presumably due to decreased effort. Under the present experimental paradigm, this effect did not occur; nor were three-response sequences requiring double alternation (LRL and RLR) emitted at lower frequencies than the other sequences. In the two-response sequence group, the possibility was explored that LR and RL sequences might have been emitted with less sensitivity to the sequence-level contingencies than LL and RR: A check of the final sessions in each subcondition showed that in about half the subconditions, LL and RR emission rates were at the extremes, with LR and RL distinctly closer to each other in the range. In only two or three instances could the converse be said to hold (i.e., the LR and RL rates at the extremes). For the three-response sequence rats, a possibly corresponding effect was the occasional emission of sequences such that those containing the most L or R responses were the

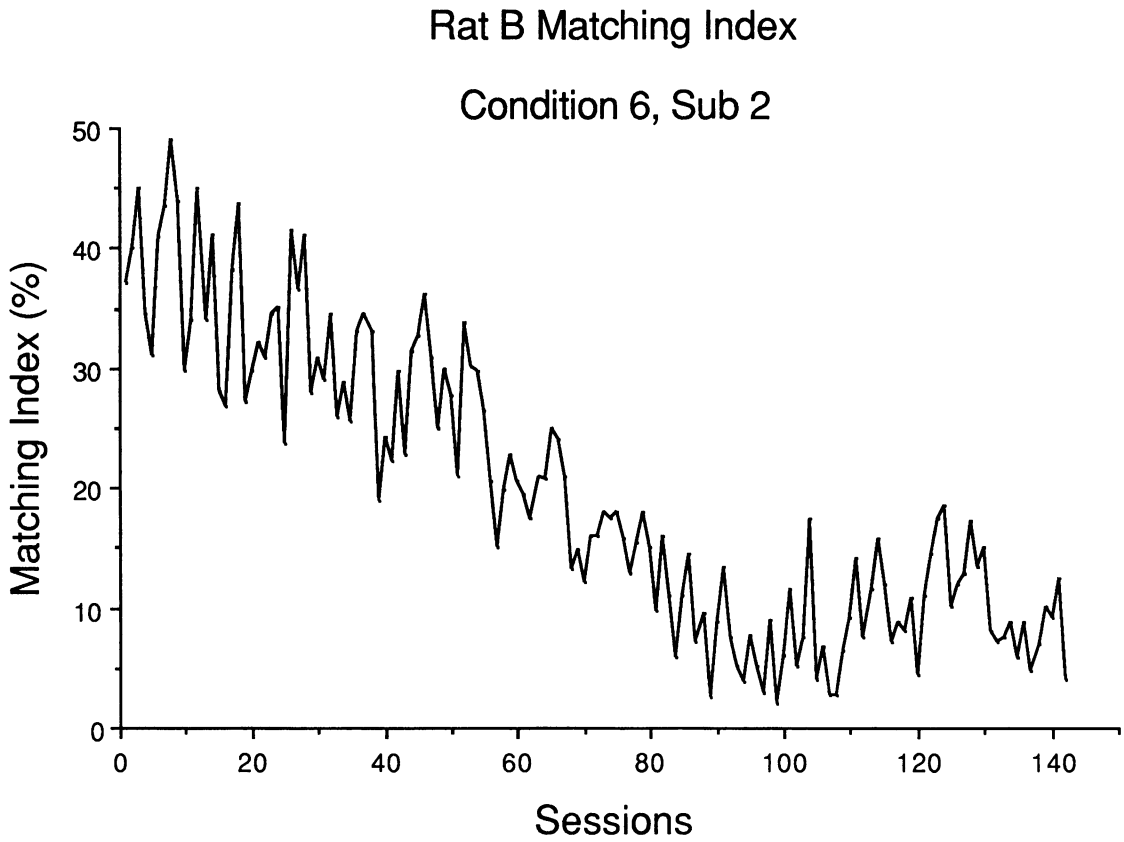

Fig. 3. Sequence matching index versus sessions in Experiment 1 for Rat B, Subcondition 2. The matching index is the difference from perfect sequence matching for each sequence, averaged across all sequences for each session. Lower index results indicate better sequence matching; a difference of zero would mean perfect sequence matching.

two different classes of reinforced sequences. Thus, sometimes the emission rates of LLL, LLR, LRL, and RLL varied together with the sequence-level contingencies, with the rates of the other four sequences moving in the opposite direction.

Conditional Probability Analyses

A first-order sequential (or transitional) probability analysis was performed on the data from the conditional probability sessions following the approach of Bakeman and Gottman (1986). Using their methods, the actual order of emission of the sequences could be compared to the order expected by chance. The obtained frequencies with which sequences immediately followed each other (Lag 1 only) were compared with the pairing frequencies expected from chance as follows: The chance frequency proportion was calculated and subtracted from the obtained proportion; the result was then multiplied by a normalization factor to enable comparison across sequences. Positive differences indicate more instances of a pair (in the given order) than expected by chance.

In the two-response sequence regular-lever Subcondition 2, the timeout responses that could occur between emissions of correctly executed sequences surely interfered with any potential order effects, and few were observed. Subcondition 5 (Figure 4) was notably different. In this subcondition, in all possible cases, sequences tended not to be repeated immediately; that is, the LL-LL, LR-LR, RL-RL, and RR-RR patterns were all less likely than chance. Although the number of observations was not quite sufficient to justify inferential statistics on these data, these patterns are suggestive. As a numerical example, the actual number of LL-LL patterns for Rat B was 11, whereas the expected number was 22. However, the uniformity of this nonrepetition effect

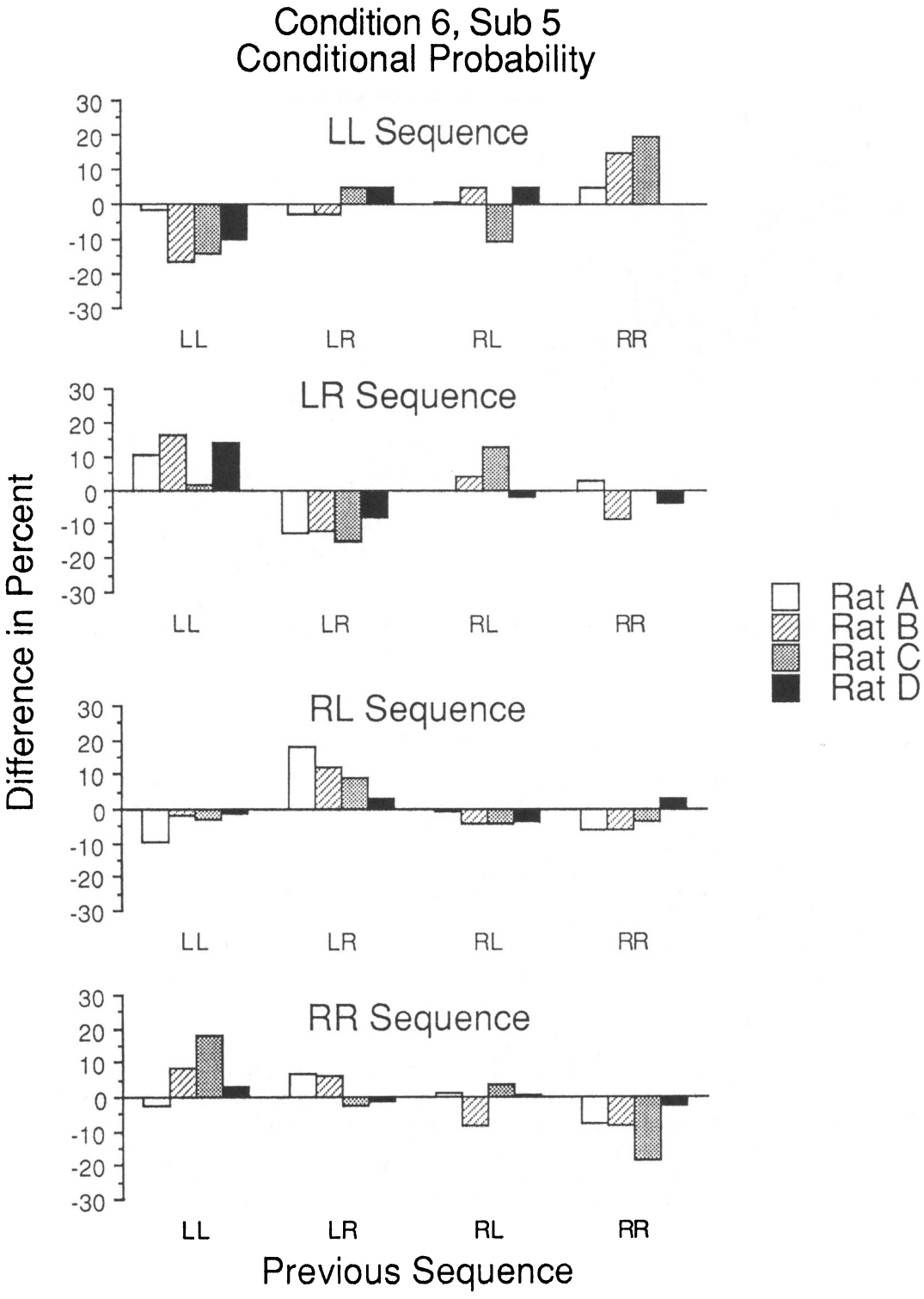

Fig. 4. Experiment 1, Condition 6, Subcondition 5. Differences between expected and obtained conditional probability for each sequence in ordered pairing with every other sequence. Positive differences indicate more occurrences of the pair than expected by chance; differences near zero indicate chance patterning.

across rats may be taken as more important than the absolute differences. Figure 4 shows several other consistent patterns: For example, sequences ending in L were more likely to precede an LR emission.

For the three-response sequence rats in Subcondition 4, relatively few instances of consistent patterns occurred. The most interesting finding was that, once again, sequences tended not to be repeated immediately, although the effect was not as strong as for the two-response sequence rats: 72% of the time sequences were repeated with frequencies below those expected by chance.

Discussion

The results of this study demonstrate that with these procedures, a minimum spacing of 5 s for regular levers and a corresponding 7-s spacing for retractable levers did not result in consistent sequence matching even with two-response sequences. Instead, results were intermediate between response matching and sequence matching. The sequence-level contingencies were clearly influential in most subconditions for the two-response sequence rats; they were much less effective in the three-response sequence group. Finally, the retractable levers only slightly facilitated the occurrence of sequence conditionability; in the case of the two-response sequence group, the moderately skewed reinforcement probabilities featured in both retractable-lever subconditions may have made detection of such effects more difficult. It is also possible that the 7-s spacing was too long to provide a good standard of comparison for the 5-s spacing in the regular-lever subconditions.

EXPERIMENT 2

Experiment 2 was a parametric study designed to find the threshold for retractable-lever sequence matching with two-response sequences only. Based on the assumption that the threshold, should one exist, must be between 0 and 7 s, Experiment 2 replicated the 7-s minimum interresponse spacing of Experiment 1 and then tested shorter spacings down to 4 s, which is close to the practical limit of the Lafayette retractable levers.

This experiment extended Experiment 1 in several ways. First, extensive training was used in Experiment 1 to develop unbiased spaced responding to start off the main experimental condition. In Experiment 2, in which only retractable levers were used, no special training was provided. In addition, reinforcement rate was controlled across all conditions.

Table 2

Experiment 2: Scheduled sequence relative reinforcement rates and spacing.

Condition	LL and LR	RL and RR	Spacing (s)
1	.10 (.05 each)	.90 (.45 each)	7
2	.90 (.45 each)	.10 (.05 each)	6
3	.10 (.05 each)	.90 (.45 each)	4
4	.90 (.45 each)	.10 (.05 each)	7

Method

Subjects and Apparatus

Four individually housed, male Sprague-Dawley Holtzman rats participated. One of the rats (Rat Y) was experimentally naive; the others had been used in an undergraduate laboratory course. As before, all rats were maintained at about 85% of their free-feeding weights, with water freely available in the home cages. The rats were about 6 months old at the start of this study.

The apparatus was the same as that used at the end of Experiment 1.

Procedure

Lever pressing was shaped in the experimentally naive rat, and all rats were exposed to the four conditions described in Table 2. The basic procedure was identical to that for the retractable-lever subconditions of Experiment 1. Conditions 1 and 4, in fact, replicated those subconditions with the exception of the sequence reinforcement probabilities: Only the 90%/10% reinforcement probabilities were used in this experiment, to enable easier determination of whether response or sequence matching was obtained. Sequence spacing was decreased in Conditions 2 and 3, and the experiment ended with a return to the spacing of Condition 1 to check for order and practice effects.

Because of the short spacing in Condition 3, a few minor changes from the general procedures were required. First, an overall VI 65-s (instead of 60-s) schedule was used to maintain a constant reinforcement rate, and the duration of houselight blinking used for

sequence demarcation was shortened from 3 s to 2 s. Similarly, the stability criteria were modified slightly in Conditions 2 and 3. In Condition 2, the sequence emissions per minute across the final nine sessions had to be within about 0.13 instead of 0.10, to allow for the increased rates, and in Condition 3, this limit was raised to 0.16. In other respects, stability criteria were identical to those used for the retractable lever sessions of Experiment 1, Condition 6. Procedures for conditional probability data acquisition were also identical and were applied in Condition 3.

Sessions were conducted at the same time each day, 6 to 7 days per week. As in Experiment 1, sessions were 60 min long, and were preceded by a 1-min timeout period. The number of sessions in each condition is listed in Appendix 2.

Results

Figure 5 displays the response matching graphs for each rat. (Absolute data are in Appendix 2.) Very marked sequence conditionability is suggested by the patterns of response distribution (see Table 2), with correspondingly poor response matching. The percentage differences are similar across all conditions, however. In addition, the extent of the skew, although close, is still not enough to match the 20% expected if perfect sequence matching were occurring; instead, the results are intermediate.

The dynamic measure of the sequence matching index was calculated for all rats as in Experiment 1. In nearly all cases, trends similar to that shown in Figure 3 occurred, but these trends were of smaller magnitude and duration. As discussed previously, the very existence of these trends indicate sensitivity to the sequence-level contingencies.

Figure 6 presents the conditional probability results for Condition 3. Marked and usually identical patterns are apparent for all rats: In 69% of the cases, data for a sequence pattern were uniformly positive or negative across subjects. This level of uniformity compares to a 50% level in Experiment 1, in which many differences were of smaller magnitude (an average absolute difference of 11.4% compared to 6.7% for the earlier data). Although the nonrepetition of sequences is replicated in Figure 6, other patterns do not always match those suggested in the earlier results. However, the sequence reinforcement probabilities were not identical.

Inferential statistics on these data were justified according to Bakeman and Gottman's (1986) recommendations for the minimum number of observations, and significance tests determined that about one third of these differences from chance levels were statistically significant. The RL-RR and RR-RR patterns are two examples that were significant at high levels for all rats. As an example of a randomly chosen numerical translation of these conditional probability differences, Rat Y's 7% difference for the LL-RR sequence pattern corresponds to 21 actual LL-RR emissions compared to the 11 expected, out of a total of 27 possible (because only 27 LL sequences were emitted).

An analysis of reinforcement effects in these raw data found that the probability of a reinforced response initiating the next sequence was not more likely than chance. For Rat S, distribution of the first response in a sequence immediately following reinforcement matched the proportions of L and R responses emitted overall, regardless of whether an L or R response had been reinforced. However, for the other 3 rats, the first response after reinforcement was more likely than chance to be an R response. For these rats, L responses constituted about a third of all responding, but they led off postreinforcement sequences only 0% to 17% of all opportunities. Within this constraint, there was some tendency for L responses to be more likely after L reinforcement deliveries, but it was small.

In general, the results in Conditions 1 and 4 replicated reasonably well. A check of response rates, however, revealed that Rats M and R exhibited lower rates in Condition 4, with final rates only about 75% of those initially seen. Despite this, reinforcement rate stability across conditions was adequate, as calculated from the final 6-day averages. For most rats, overall reinforcement rates for Conditions 2 and 3 did tend to be somewhat higher. They were most consistent for Rat Y, which obtained reinforcement rates, in order, of 0.65, 0.63, 0.66, and 0.66 reinforcers per minute. The rat with the most extreme difference was Rat R, with rates of 0.54, 0.56, 0.67, and 0.50. (This rat was 1 of the 2 whose Condition 4 rates never recovered to Condition 1 levels.)

Finally, as in Experiment 1, a check con-

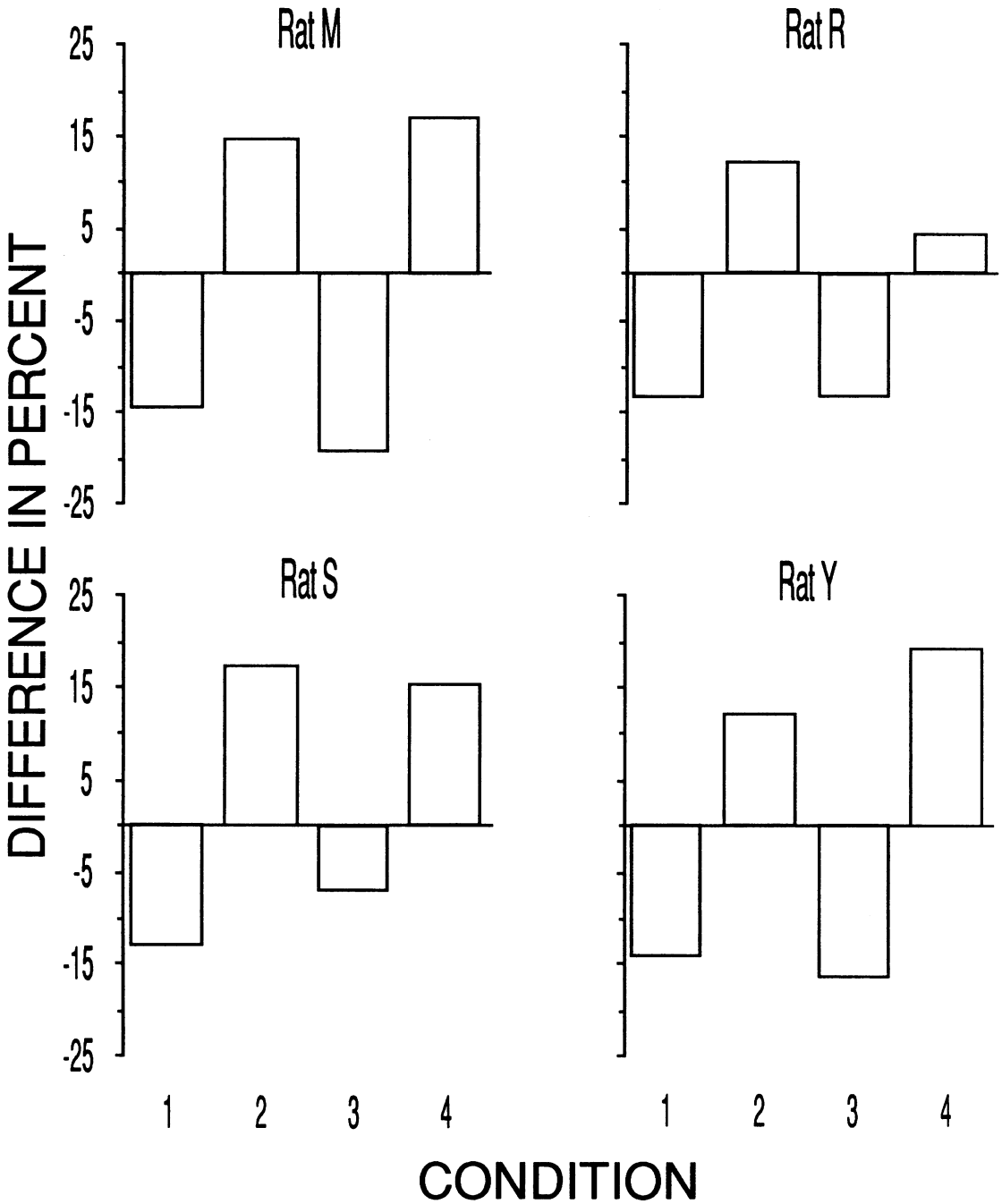

Fig. 5. Response matching graphs showing the difference between L response-rate proportion and L reinforcement-rate proportion in Experiment 2. Positive differences indicate higher L response rates than predicted by response matching; differences near zero indicate good response matching.

firmed that the LL and RR sequence emission rates tended to be at the extremes, with LR and RL intermediate (see Table 3, which provides the average proportions for the last five sessions of each condition). In fact, LL and RR usually matched the corresponding reinforcement proportions of 45% or 5% well; it was the sequences with alternations that pre-

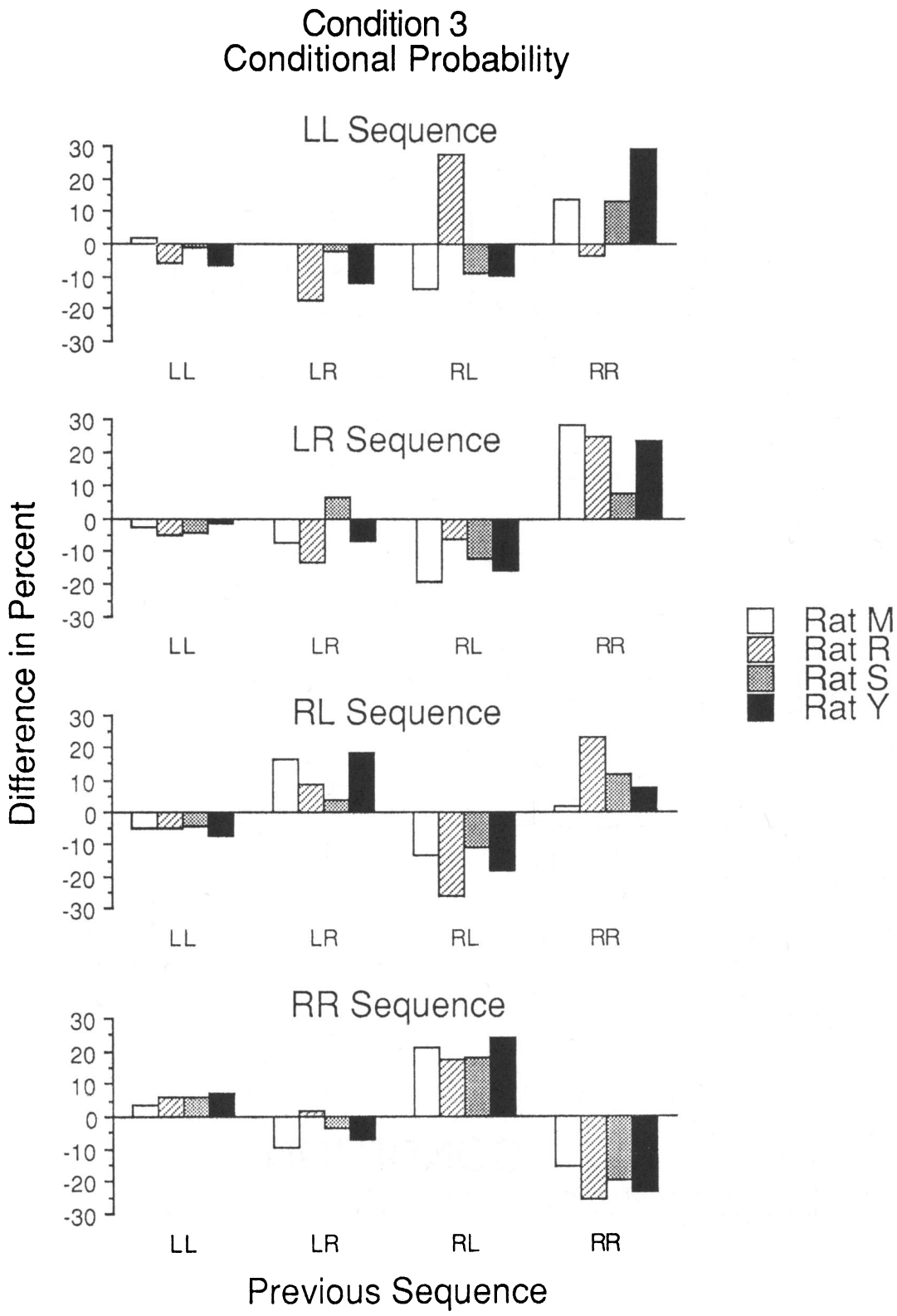

Fig. 6. Experiment 2, Condition 3. Differences between expected and obtained conditional probability for each sequence in ordered pairing with every other sequence. Positive differences indicate more occurrences of the pair than expected by chance; differences near zero indicate chance patterning.

Table 3
Experiment 2: Obtained LL/LR/RL/RR sequence percentages.

Rat	Condition 1	2	3	4
M	12/22/24/41	37/31/21/11	5/19/30/46	42/23/27/8
R	8/24/33/35	35/28/26/11	9/17/30/44	33/25/30/12
S	13/27/35/25	38/36/19/8	20/17/34/29	46/29/14/10
Y	8/22/31/39	34/24/30/12	9/18/31/43	44/32/16/8

vented the occurrence of uniformly good sequence matching. However, in only 2 of 16 cases were the LR and RL proportions so close to each other as to be within 3%, whereas 12 of the 16 differences were at 6% or greater. The average difference was 9.8%. With respect to the response effort effect, Table 3 shows that even in Condition 3 with its short 4-s spacing, LR and RL were not emitted at lower combined rates than LL and RR.

Discussion

A comparison of the response matching figures shows that, considering that the sequence reinforcement probabilities were different, the results of Conditions 1 and 4 replicated the two-response sequence Subconditions 4 and 5 of Experiment 1 adequately. That Condition 1 replicated these results despite no lengthy training shows that, with retractable levers at least, training seems to have little effect. Sequence conditionability showed slight, if any, improvement from this level with the shorter spacing in Conditions 2 and 3. Nonetheless, the overall response matching results in Experiment 2 are clearly more in the direction of sequence matching than response matching. Between the two, then, these experiments begin to quantify the effects of reinforcement delay on this type of potential behavioral unit.

Conditions 1 and 4 also replicated each other fairly well, even though 2 rats did not recover their initial response rates. Order effects, then, were not very strong, and practice at shorter intervals did not enable higher sequence conditionability in Condition 4 than in Condition 1.

Perhaps the most interesting data from Experiment 2 were the conditional probability results. Whereas the response matching data indicated almost no effect from shortening the required spacing, comparison of the conditional probability graphs from both experiments suggests that these effects may not have been so minor after all. Perhaps this type of approach will eventually enable a new analysis of the molar–molecular problem: What controls these marked patterns—these sequences of sequences? And how are they related to delay of reinforcement?

GENERAL DISCUSSION

Overall, these experiments provide the beginnings of a sequence matching dimension for sequences of spaced responses, with implications for delay of reinforcement, behavioral units, and the matching law. At the range of delay values investigated, differences in sequence conditionability were clearly present. Response matching was best in the three-response sequence conditions and poorest in the two-response sequence retractable-lever ones, and vice versa for sequence matching; and the conditional probability results showed the strongest patterns for the shortest spaced two-response sequence retractable-lever condition. Thus, increased sequence spacing and number of responses reduced sequence coherence and obedience to the matching law. These results supplement previous findings about the COD value necessary in concurrent schedules to keep switching responses independent. As mentioned in the introduction, typical values for rats have been found to be in the range of 5 to 10 s (de Villiers, 1977). The present study explored this threshold area and supports the conclusion that CODs at the high end of this range are sufficient to prevent consistently good sequence matching—but not sufficient to prevent any influence of a sequence-level contingency. Any reinterpretation of the literature on concurrent schedules might check for possible adventitious effects of this nature. Analogous effects can be expected in related literatures such as those on response patterning and on sequences. It should be noted in this context that even the disruptive effect of in-

correctly spaced responses in the regular-level subconditions did not prevent sequence conditionability almost as good as that in corresponding retractable-lever sessions.

Behavioral Units

Determination of the behavioral unit in these studies must be attempted cautiously. Stubbs et al. (1987) pointed out that even the clear sequence matching found in their main experiment did not definitively establish that the sequences were units. The pigeons' behavior may simply have been responsive to the general sequence-level contingencies. That is, the differential contingencies on the first L or R peck in a sequence may have been effective without ever really producing coherent, functional sequences. A second experiment that reinforced the four possible two-response sequences with different probabilities for each found the same sequence matching as in the main experiment, making this explanation less tenable. Further, responding of this nature in two-response sequence conditions would produce LR and RL sequence rates that were identical, because the overall probability of L or R responses would be adjusted without regard to their combination in the sequences. Thus, because only the delayed reinforcement for the first response in a sequence differed from 50/50, the overall probability of L responses might increase somewhat to, say, 60% instead of the 50% predicted from the immediate reinforcement of the final response in the sequence. The probability for the sequences would then be .36 (.6 × .6) for LL, .24 (.6 × .4) for LR *and* RL, and .16 (.4 × .4) for RR, meaning that the LR and RL sequences should always be emitted at similar rates under this model. (Discriminability effects could produce similar results.) This is one of the intermediate models possible between the two extremes of perfect sequence-level matching and response-level matching. Put another way, reinforcement could potentially affect only the last response in the sequences; affect both responses, but not as a unit; and affect both responses as a coherent unit.

In this study, neither clear sequence matching nor clear response matching occurred; rather, the results were intermediate. However, although the LR and RL sequences were less widely separated than the LL and RR in the two-response sequence conditions, they were still clearly differentiated (see Table 3). Do none of these three models apply? Is the unit idea inapplicable here? In any event, one conclusion follows: In comparison to Stubbs et al.'s (1987) demonstration of sequences as units, delay effects here were presumably strong enough to prevent similar results. In other experimental contexts, reinforcement rate has also been an important variable (e.g., Luck, Colgrove, & Neuringer, 1988), but at the reinforcement rate ranges explored in Experiment 1 no comparable effects were noted.

Conditional Probability

The conditional probability analyses produced some of the most pertinent findings. Analogous to the two-response sequence results of Stubbs et al. (1987), sequences tended not to be emitted twice in a row, demonstrating sensitivity to more molar-level contingencies: A repeated sequence was seldom reinforced. In addition, and also as suggested by Stubbs et al. for their two-response sequence pigeons, consistent patterns of responding emerged in the present two-response sequence conditions, especially in Experiment 2, Condition 3. These indications of sequential effects are not surprising. Such effects are found for individual responses in ordinary schedules (e.g., Weiss, Laties, Siegel, & Goldstein, 1966, for DRL; see also Shimp, 1981), so that if the sequences are semiunitary, comparable effects should presumably occur. Exploring the origins and nature of these patterns may prove useful. Why Stubbs et al. did not find much evidence of patterning in their three-response sequence birds, considering the short spacing, is puzzling.

With regard to the nonrepetition effect, Schwartz has shown that reinforced behavioral patterns tend to be repeated, even when other patterns would also be reinforced (e.g., Schwartz, 1981; see also Luck et al., 1988). When the contingencies are even mildly against it, however, such stereotypy seldom occurs; in fact, the opposite effect may appear, as responses or sequences that are reinforced become less likely to be immediately emitted (e.g., Killeen, 1970; Page & Neuringer, 1985). This nonrepetition effect was observed both in the study of Stubbs et al. (1987) and in the present study.

Theoretical Comments

The results of the present study add to the data base relevant to the molar–molecular and contiguity–correlation controversies. In ordinary concurrent-schedule research, these issues revolve around whether response matching occurs independently of any molecular-level, close contiguity control, or if matching is only a result of order at the molecular level. Research intended to isolate the molecular patterns, if they exist, has not only failed to be conclusive but has led to an extensive literature debating the inferences that can be drawn from these data (e.g., Heyman & Herrnstein, 1986; Hinson & Staddon, 1983; Nevin, 1982; Silberberg & Ziriax, 1985).

Through demonstrating the importance of reinforcement contiguity, the current results can be taken as support for the molecular side of this debate. However, the evidence that the sequences were sometimes themselves under sequential control is a more molar-level finding. In addition, to the extent that sequence matching occurred regardless of molecular-level patterning, molar correlation accounts would receive support (see Stubbs et al., 1987). The regularities found in the analysis of the raw conditional probability data could be interpreted in either direction.

Quantitatively, no current models have been designed to account for results using the present sort of procedure, although many are potentially applicable. Probably the most promising group is the set of models designed to account for concurrent-schedule responding (see Commons, Herrnstein, & Rachlin, 1982). A combination of one of these models with one that explicitly accounts for delay of reinforcement (e.g., Killeen, 1982; Mazur, 1984, 1987; McDowell, 1987) may ultimately find the most success. The discounting-function approach to accounting for delay effects is also promising (see Hackenberg & Hineline, 1992, for a recent summary).

A few other connections are worth mentioning. First, further research focused on the interaction between the total delay from the first response in a sequence to reinforcement at the end, and the number of responses required in the sequence, will address a longstanding question: Does it make a difference whether responses are required? Past research using other experimental paradigms is inconsistent on this point (Mazur, 1986; Morgan, 1970). Second, looking at timing research and the effects of sequence demarcation stimuli, Marcucella (1974) found that even when a signal cued the end of a DRL interval, rats' behavior did not come under its control. The current procedures can readily be extended to address these questions.

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APPENDIX 1

Experiment 1, absolute measures: Number of sessions and final left response[a] and reinforcement rates (per minute).

	Condition 6 Subcondition				
Rat	1	2	3	4	5
A	42	65	37	20	25
	3.61	1.62	2.29	2.27	2.61
	0.21	0.10	0.15	0.22	0.23
B	60	143	NA	46	28
	3.04	1.84		2.78	4.14
	0.06	0.20		0.27	0.28
C	37	26	46	49	24
	3.46	3.01	3.04	2.76	2.78
	0.18	0.17	0.15	0.25	0.21
D	47	33	50	20	28
	2.94	1.64	2.62	2.75	2.73
	0.14	0.06	0.14	0.22	0.20
E	41	84	31	45	
	2.13	2.48	2.30	1.94	
	0.03	0.04	0.09	0.07	
F	43	52	34	34	
	0.63	2.50	3.09	3.39	
	0.01	0.06	0.11	0.12	
G	48	57	53	57	
	2.53	2.68	4.09	3.45	
	0.03	0.02	0.12	0.09	
H	75	41	85	39	
	1.38	1.35	2.76	3.33	
	0.03	0.03	0.11	0.13	

[a] Excludes timeout responses (see text).

APPENDIX 2

Experiment 2, absolute measures: Number of sessions and final left response and reinforcement rates (per minute).

	Condition			
Rat	1	2	3	4
M	29	31	36	22
	2.55	5.16	2.69	3.42
	0.28	0.32	0.32	0.27
R	39	28	29[a]	29
	2.41	3.76	2.74	2.84
	0.27	0.28	0.31	0.28
S	26	27	26	34
	3.03	5.49	5.18	4.60
	0.30	0.29	0.34	0.31
Y	29	22	22	31
	2.80	5.21	3.90	4.65
	0.32	0.31	0.32	0.32

[a] A dispenser pellet jam had strong lingering effects on responding for five of these sessions; these sessions were not included in data analysis.