Some further observations on serial enumeration and categorical flexibility

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Rats were runway-trained in a variety of serial discriminations that involved three different reward outcomes: Noyes pellets (R), a Kellogg's Corn Pop (R'), and 30 sec of confinement in an unbaited goal area (N). Each of three groups experienced a series that consisted of a single non-rewarded trip down the runway, irregularly mixed with a longer series that for one group ($n = 3$) consisted of three trips rewarded with the pellets, followed by a terminal nonrewarded trip (RRRN/N). A second group ($n = 6$) had the single N series mixed with a series that included an initial trip rewarded with a Pop, and three subsequent trips rewarded with pellets, pellets, and nothing, respectively (R'RRN/N). The remaining group was trained with an RRN/N series pair. The interval between trips within a series was about 20 sec, and the interval between series was about 10 min. All rats developed strong, accurate anticipation of the terminal nonreward event of the longer series. In a 4-day transfer shift phase, a matched one-half of the rats originally trained R'RRN/N were shifted to a new series pair, RRRN/NRRRN, as were all the animals trained RRN/N. The remaining one-half of the matched rats were shifted to RRN/NRRN, as were the animals originally trained on the RRRN/N series pair. The transfer to the new series was plainly more powerful in animals initially trained with the R'RRN series than it was in either of the control groups. This shift result is taken to mean that rats classified the differing motivational events of the R'RRN series into at least three numerical categories: (1) one R', (2) two Rs, and (3) three rewards.

In any instrumental learning situation that involves series of reward events, the number of preceding events may become a reliable predictor of upcoming events. Consider a procedure in which rats are runway-trained on the series RRN—two rewarded (R) runs are always followed by a nonrewarded (N) run. If the animals also experience, equally often, the series NRRN, unaccompanied by some special set of events distinguishing it from the RRN series, the number of runs and various temporal cues (e.g., time since the first run) are not relevant predictors of the terminal nonreward in the series. A pair of rewarded runs, however, reliably predicts nonreward in both series. Rats react to this sort of training by running relatively fast to all series events except the terminal nonreward, to which they run slowly (Burns & Sanders, 1987; Capaldi & Miller, 1988).

There are, of course, attributes other than number that may be applied within any string of reward events. Capaldi and Miller (1988) imagined that rats assign such events to categories on the basis of their sensory attributes (e.g., "sweet," "edible," "crunchy") and that the animals enumerate, or assign number tags to, events placed within those categories. Furthermore, rats were

expected to show some flexibility in their categorization by including a given reward in more than one category (e.g., sweet and crunchy). The enumeration within a category also was expected to be flexible.

In their Experiment 5, Capaldi and Miller trained rats on the series R'RRN and on a single N series, R'RRN/N. A Kellogg's Corn Pop was R' and standard Noyes pellets were the R events. Among other things, the rats in such a problem may have ignored the differing sensory attributes of the rewards and counted the rewards simply as three rewards, or they may have categorized on the basis of some set of sensory qualities and counted one Pop and two pellets. If animals are capable of categorical flexibility, they would have enumerated the rewards *both* ways, and shifts to different series following training with R'RRN/N implied that they might have done so.

The rats were shifted to a problem that required their enumerating either two-reward events (RRN/NRRN) or three-reward events (RRRN/NRRRN). Animals in each shift condition were given each of their two shift series three times a day for 3 days, and both shifted groups developed slower running to the terminal nonrewards of their series during the first shift day.

It is possible that the ease of adjustment to the shifted conditions was because the rats had learned to separately count both three and two rewards before the shift, but a better reckoning may be that animals trained in one problem involving a number discrimination readily learn any new number discrimination. This second possibility was suggested to us in part by the finding that rats quickly

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learn simultaneous number discriminations in these serial tasks (Burns & Sanders, 1987).

Whether Capaldi and Miller's (1988, Experiment 5) findings showed categorical flexibility or simply showed rapid intradimensional shifting is a question that may be answered with appropriate controls to which the shifted animals can be compared. Here we report an experiment in which rats were trained with R'RRN/N and shifted to either RRN/NRRN or RRRN/NRRRN (as Capaldi & Miller had done). In one additional control group, our rats were initially trained on a problem that required counting two-reward events (RRN/N) and were then shifted to a three-reward problem (RRRN/NRRRN). A second control was trained initially on a three-reward problem (RRRN/N) and subsequently on a two-reward problem (RRN/NRRN).

If animals trained on the R'RRN series categorize the reward events (1) as one R', (2) as two Rs, and (3) as three rewards, their performance on a subsequent three-reward problem would be superior to that of controls shifted to a three-reward problem after training with only two rewards. For similar reasons, control animals trained initially with three rewards would be inferior on a subsequent two-reward problem to rats trained first with R'RRN. Rapid intradimensional transfer would be the best account for comparable shift performance among the groups.

METHOD

Subjects

The subjects were 12 naive male rats (Holtzman Co., Madison, Wisconsin). The animals were about 65 days old when they arrived at the laboratory.

Apparatus

We used a black, L-shaped runway that was 233.7 cm long and covered with vented clear plastic. Measures of total running times were taken from a Standard timer that was activated when the manually operated start door was opened and stopped when the rat crossed a photocell mounted 195.6 cm beyond it. Entry into the goal area was marked by a right turn, 182.9 cm beyond the start door, that lead to an aluminum goal cup, 7.62 cm in diameter and 4.45 cm deep.

Procedure

When they arrived, all animals were housed in individual living cages in the room that contained the runway. During the entire experiment, the rats had free access to water, and were given 14 g of Purina Rodent Chow on each day that was followed by a training day. They were trained on weekdays only, and were given 20 g of chow on days not followed by training days. For the first 3 days in the lab, each rat was handled for about 1 min and allowed about 15 min on a walled exercise table with other animals. There followed 2 days of runway exploration during which each rat was allowed to explore the entire runway for 5 min once each day. Scattered throughout the runway were two Kellogg's Corn Pops and four .045-g standard Noyes pellets, the rewards to be used during primary training.

For all subjects, primary training involved two series each day that consisted of a single nonrewarded (N) run. For one group ($n = 6$), the initial run of another series, which also occurred twice a day, ended in reward (a single Pop) and was followed by two

successive runs on which six Noyes pellets were the reward. The series terminated with a nonrewarded run. We will call the Pop R' and the pellets R so that the two series may be represented as R'RRN and N (R'RRN/N). A second group ($n = 3$) was trained on the series RRN and N (RRN/N), and a third group ($n = 3$) was trained RRRN/N.

The rats were assigned to groups at random, and also were assigned to training squads of 4 animals each so that each squad contained 2 rats trained on the R'RRN/N series pair and 1 rat trained on each of the other series pairs. The order of training the squads and the animals within squads was determined randomly each day. The longer of the two series is symbolized as A and the single N series as B. The order in which a given rat had the four daily series was either ABBA or BAAB, and, on any given day, half the rats from each training squad were trained on each series order (that determination also was random each day). All runs of a series were administered successively to a given rat before another rat ran—a procedure that made for an interval of about 20 sec among the runs of a series. All animals in a training squad were administered an entire series before any other animal was given the next series, creating an interval of about 10 min between series.

A run began with the opening of the start door about 2 sec after the rat was placed in the start area, and it terminated when the reward was consumed, or after 30 sec in the unbaited goal area on nonrewarded runs. Immediately after training each day, the rats were placed on the exercise table for about 15 min before being returned to the living cage that contained their daily ration. All intervals between runs and between series were spent in the living cage with water available. For a nonrewarded run, the runway preparation was as similar as possible to the procedure on rewarded runs, including a sham goal-cup loading.

After 21 days of primary training, the rats trained R'RRN/N were matched on the basis of the difference between their average times on the terminal N run and the preceding R run of the R'RRN series, and they were assigned to one of two transfer conditions. In one condition ($n = 3$), the series pair was RRN/NRRN, a two-reward problem. The other transfer condition ($n = 3$) was RRRN/NRRRN, a three-reward problem. The group initially trained RRN/N was shifted to RRRN/NRRRN, and the group initially trained RRRN/N was shifted to RRN/NRRN. The procedure during the shift was the same as during primary training except, of course, that the series were altered and that each series was administered once rather than twice each day. Transfer training continued 4 days.

RESULTS

All raw times were transformed [$x = \log(x)$] for analysis. Plotted in Figure 1 are average times on each run of the various training series in 3-day blocks. The unconnected points in Figure 1 represent group averages for the single N series. For conformity, the terminal nonrewarded run of the longer series is always depicted as Run 4.

It is important to note that, in primary training, animals in all training conditions developed pronounced anticipation of the terminal nonreward event in the longer series. Analyses of variance that included only the runs common to the three longer series (Runs 2, 3, & 4) produced significant effects of runs on Dayblocks 3-7 [$F(2,18) = 29.75; 67.34; 206.23; 167.46; \& 234.68$, respectively; $p < .01$]. There were no other significant main effects, nor were there interactions, in these analyses. The Bonferroni t statistic ($p < .05$) used to evaluate the run means

Figure 1. Mean transformed run times in blocks of 3 days for the R'RRN, RRRN, and RRN series used in primary training. Group averages for the single N series are shown as unconnected points, and the terminal nonrewarded run of the longer series is shown as Run 4, irrespective of the actual number of runs in a series.

showed that, in each dayblock, times on the terminal non-rewarded run were significantly greater than on either of the preceding rewarded runs ($k = 3$, $df = 18$), each of which always failed to differ from the other. Additional analyses to look for group differences on the single N series yielded no reliable effects.

Adjustment to the shift conditions was noticeably less problematic for the animals trained previously on the R'RRN series than for controls trained originally with either RRN or RRRN. Figure 2 depicts the average times on each series run during transfer training. The two groups shifted to a two-reward problem (those trained originally with either the R'RRN/N series or the RRRN/N series) are shown in the left panel of Figure 2. The groups shifted to the three-reward problem (those trained originally with either the R'RRN/N series or the RRN/N series) are shown in the right panel.

An analysis of the common series runs for groups shifted to a two-reward problem produced a reliable groups $\times$ runs interaction [$F(2,8) = 5.57$, $p < .05$], which was similar in form for both RRN and NRRN transfer series ($F < 1$). Evaluation of the interaction ($k = 15$, $df = 12$) showed that approach to the goal for the group trained originally with the R'RRN series was significantly slower on the terminal nonrewarded run of the two-reward transfer series than was approach for controls originally trained on a simple three-reward problem. No other pairwise differences in the interaction were reliable.

When the common series runs for groups shifted to the three-reward problem were analyzed, a significant groups $\times$ runs $\times$ series interaction [$F(3,12) = 6.71$, $p < .01$] suggested that training with R'RRN facilitated anticipation in the RRRN shift series, but not in the shift series that began with a nonrewarded run (NRRRN). There was no evidence of group differences in an analysis of the over-

all NRRRN shift series performance ($F_s < 1$). Bonferroni comparisons ($k = 10$, $df = 16$) of the significant main effect of runs [$F(4,16) = 7.72$, $p < .01$] in that analysis showed only that running was slower to the terminal nonreward of the series than to any other element.

Statistical evaluation of performance on the RRRN shift series produced a main effect of runs [$F(3,12) = 29.49$, $p < .01$] and a groups $\times$ runs interaction [$F(3,12) = 31.82$]. Comparisons among the interaction means ($k = 28$, $df = 16$) showed clearly that the animals trained R'RRN ran slower on the terminal run of the new RRRN series than did controls trained originally with RRN.

Figure 2. Average transformed times for each series run during shift training. The groups shifted to the RRN/NRRN series are shown in the left panel. The groups shifted to RRRN/NRRRN are shown in the right panel.

Although in the control rats' approach to the third R of the new RRRN series was slower ($M = 1.51$) than to any of their other runs in that series (average of other runs was .82), it was not significantly slower.

DISCUSSION

Animals trained on the series pairs R'RRN/N, RRN/N, or RRRN/N developed accurate anticipation of the terminal nonreward event in the longer series of every pair, and there was no indication that the degree of anticipation differed among the various series pairs. There was, however, reasonably clear evidence that what was learned differed among the series. Consideration of relative transfer to the shift series RRN/NRRN and RRRN/NRRRN warrants the following conclusions: The precise number of previously rewarded events was a characteristic of the series to which animals in all our original training conditions were sensitive. Rats trained initially on the RRN/N series accurately anticipated the terminal nonreward of the longer series (this is based upon their counting of two successive rewards), and those in the RRRN/N condition enumerated the three rewards of their series. In addition, the animals trained R'RRN/N concurrently categorized and counted the events of their series specifically as one Pop and two pellet rewards, and generally as three rewards. They showed categorical flexibility. Finally, the facility with which R'RRN experience transferred to the new number problems cannot be explained solely as rapid intradimensional shifting.

That the pure number of rewarded events of one kind or another was a dimension to which these animals attended is suggested by the irrelevance of several other possible sources of discriminative control in these problems. Capaldi and Miller (1988) have examined alternatives to a reward-counting explanation in detail, so here we only briefly outline those alternatives. Counting responses, trials, or intertrial intervals would not have led to reliable anticipation in, for example, the series pair RRN/NRRN. The number of runs, responses, and intertrial intervals in these series differ, and because the series are presented to the rat in irregular order with no other

differentiating events, the animals could not be expected to have run slower to the terminal nonreward of both series and equally faster to the preceding rewarded runs of both series. This conclusion is based on numerical information that differed in the two series. That the rats relied upon a *same/different* strategy (e.g., running slower after two comparable events in series like RRN/NRRN) is a possibility that would not explain transfer from the R'RRN series.

Timing strategies (e.g., using the time from the beginning of a series to predict the terminal nonreward) would be ineffective in situations similar to those studied here, which involve numerous changes in series durations. Another implausible non-numerical source of control, postgestational slowing, cannot explain the performance in such differing number series as RRN and RRRN.

It is now becoming clear that rats rely heavily upon number cues in situations in which we customarily study serial learning, and it seems unlikely that serial paradigms in the laboratory are the only conditions that would readily provoke enumeration by animals. This view of the rat's counting contrasts sharply with an earlier view proposed by Davis and Memmott (1982), who concluded that natural history has given the rat little reason to count, especially in "unnatural" settings.

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