A simultaneous temporal processing account of response rate

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ABSTRACT

The goal was to determine whether a signal (e.g., a click) at food availability affects timing behavior in rats. Twenty-four rats were trained on an appetitive lever-press procedure that varied on two dimensions: shape of the interreinforcer distribution (i.e., fixed-interval 60 s or random-interval 60 s) and number of signals (i.e., the presence or absence of a click at the time of reinforcer availability). The rats were randomly partitioned into one of four groups (each group had six rats): Fixed, Signaled-Fixed, Random, and Signaled-Random. The shape of the interreinforcer distribution affected the response pattern; the presence of the click affected response rate. These results provide support for a simultaneous temporal processing account of behavior.

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1. Introduction

Simultaneous temporal processing is the study of how the information from multiple time markers is integrated when they all predict availability of the same reinforcer (Church et al., 2003; Guilhardi et al., 2005). The results have shown that rats will integrate the information from multiple time markers to adjust the time at which anticipatory behavior occurs on appetitive conditioning procedures. Procedures that have been used range from those with only one time marker (where no integration is required), to those with several time markers (where the integration of multiple sources of temporal information occurs). Our goal in this paper is to use a simultaneous temporal processing approach to explain the pattern and the rate of behavior that occurs in a response-contingent procedure when the rat is given an additional time cue at the time of reinforcer availability.

The simplest interval-schedule response-contingent procedure is one in which a reinforcer is made available at a constant interval (e.g., every 60 s), and delivered contingent upon some response (e.g., a lever press). Skinner originally referred to this type of procedure as periodic reconditioning (Skinner, 1938), and it is now usually referred to as a fixed-interval schedule of reinforcement (Ferster and Skinner, 1957). In the fixed-interval schedule of reinforcement, rats have one time marker (the delivery of food) to use to predict the availability of the next food. If an additional stimulus (e.g., a click) is presented at some time between the previous food, and the next food availability (but always at the same time), the rat has two time markers it can use to predict the time of the next food availability: the previous food and the click. In this literature, the time markers that precede the reinforcer often do not occur at the same time as reinforcer availability or delivery.

The simultaneous temporal processing literature has shown that the presentation of a stimulus during the food-to-food interval produces a decrease in response rate following stimulus presentation (e.g., Dews, 1962; Meck and Church, 1984). Packet theory states that as time markers are presented, the temporal information they provide is integrated using a linear averaging rule (MacInnis, 2007). The degree to which one time marker is weighted more than another depends on multiple factors including proximity to a reinforcer. It has been shown that the closer in time a stimulus is to the reinforcer, the more weight is allocated to it (Guilhardi et al., 2005). If this is the case, it is reasonable to assume that, if a stimulus occurs at the time at which a reinforcer is made available, that signal should take much of the weight when determining how behavior should be adjusted. If much, or all, of the weight is allocated to the stimulus and not the food, the prediction would be a very low rate of response prior to food availability.

Although there have been some studies that employ a signal at the time of reinforcer availability (e.g., Mellon et al., 1995), the effect of the signal on the timing of behavior, as well as the rate of behavior, has not been comprehensively examined. In this study, we use four simple interval schedules of reinforcement to examine the effect of a stimulus that is presented at the time of reinforcer availability in a response-contingent procedure on response pattern and rate.

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2. Materials and methods

2.1. Subjects

Twenty-four experimentally naive male Sprague–Dawley rats (Taconic Laboratories, Germantown, NY) were used in the experiment. They were 30–37 days old upon arrival, and were handled daily from arrival to the onset of the experiment. Testing began 1 month after arrival. The rats were housed individually in a colony room on a 12:12 h light/dark cycle (lights off at 9:30 a.m.). Dim red light illuminated the colony room and the testing rooms. In addition to the reinforcers obtained in the experimental chambers, the rats were fed a ration of FormuLab 5008 food daily. The amount of food given following the daily testing session was adjusted to maintain the rats at 85% of the ad lib control (data for the control function obtained from Taconic Laboratories). Water was available *ad libitum* in both the home cages and the experimental chambers. The rats were tested daily at 3:00 p.m.

2.2. Apparatus

Twenty-four operant chambers (25 cm × 30 cm × 30 cm), each located inside a ventilated, noise-attenuating box (74 cm × 38 cm × 60 cm), were used in testing. Each chamber was equipped with a food cup (5 cm × 5 cm × 2 cm) and a water bottle. A magazine pellet dispenser (Model ENV-203, Med Associates, St. Albans, VT) delivered 45-mg Dustless Precision Pellets (Bio-Serv, Rodent Grain-Base Formula, Frenchtown, NJ) into the food cup that was located on the right-hand wall. Each head entry into the food cup was transduced by a LED-photocell. The food cup was centered between the two levers (Model ENV-112) that were 12 cm apart. The two levers were placed 7 cm above the grid, measured 4.5 cm wide, extended 2 cm into the box, and were 0.1 cm in height. The levers required a force of approximately 0.18 N to operate. The water bottle was mounted on the outside of the experimental chamber. Water was available through a tube that passed through a hole in the middle of the left-hand wall, opposite the food cup. A 70-dB white noise, with an onset rise time and termination fall time of 10 ms, was generated by an audio amplifier (Model ANL-926). The sound pressure level (SPL) was calibrated at the beginning of the experiment with a sound level meter (Radio Shack, catalog number 33-2055). The clicker (Model ENV-135M) was a small relay mounted on the outside of the chamber, and was used to produce an auditory click. Two Gateway Pentium computers, running the Med-PC Medstate Notation Version 2.0 (Tatham and Zurn, 1989), controlled experimental events and recorded the time at which events occurred with 2-ms resolution.

2.3. Procedure

Prior to the onset of the experiment, all rats were trained on a single session of a lever-press autoshaping protocol. At the beginning of this session the 70-dB white noise came on and one of the two levers (counterbalanced across rats) was inserted into the operant chamber. Food was delivered on a random time 120-s schedule until the first lever press. Following the first lever press the random time schedule was terminated, and the food was delivered only for each subsequent lever press. After 30 presses on the first lever, it was retracted and the other lever was inserted. After 30 presses on the second lever, the lever was retracted, the white noise was terminated, and the session ended. If the rats did not complete the 60 presses within an hour, the session was terminated, they were removed from the chamber, and retrained later that day. This occurred for two of the 24 rats. They completed the second training session well within the hour limit.

Fig. 1 shows the procedure used in this experiment. The basic cycle structure was a 60-s food-to-food cycle. At the beginning of each session, a 70-dB white noise came on and stayed on until the end of the session. For the two fixed-interval groups the first lever press 60 s following the previous food delivery delivered the food. For the two random-interval groups, the first lever press a random number of seconds following the previous food delivery would deliver the food. An exponential distribution was used to determine the interreinforcer interval, so that there was a constant probability of food becoming available, with an average of 60 s between delivery and the next food availability. Immediately after food was delivered the next cycle began.

In the two signaled groups, a click was presented at the time of reinforcer availability. The click occurred 60 s following food delivery for the fixed group, and occurred on average 60 s later in the random group. The presentation of the click was not contingent on any response from the rat.

The rats were randomly partitioned among the four groups, with six rats in each group. The between-group variables were interval duration distribution and signal presentation. The names of the groups were determined by interval distribution (fixed and random) and signal presentation: Groups Fixed, Signaled-Fixed, Random, and Signaled-Random. Each session lasted for 120 trials, or 125 min, whichever came first. The rats were trained for 50 sessions.

2.4. Data analysis

The data analyses were based on the last 10 sessions of training. Response gradients were first calculated for each rat individually, by taking the number of responses in each 1-s bin of the 60-s cycle, calculating the average response rate in that bin, and dividing it by
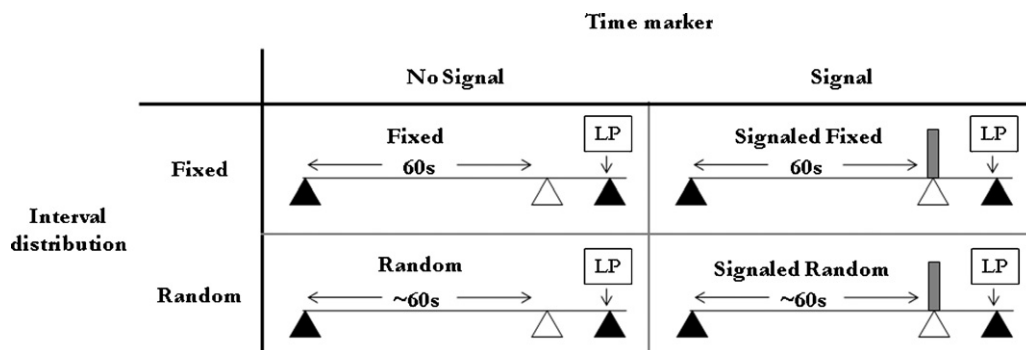

Fig. 1. The procedure implemented in this study. The top row of the figure shows the procedures for the Fixed and Signaled-Fixed groups. The bottom row of the figure shows the procedures for the Random and Signaled-Random groups. Food availability and food delivery are indicated by the white and black triangles, respectively. The click is indicated by the gray rectangle, the lever press response that delivers the food is indicated by the box with the arrow in which there is the abbreviation LP.

the number of opportunities the rat had to respond at that time. (This step is critical for the calculation of the response gradients for the two random groups, because the cycles were not all the same length.) The first 3 s of the interval were not included in the presentation of the gradients as they include reaction to food delivery that is not relevant to the points discussed here.

The curvature index was calculated on a cycle-by-cycle basis using the method described by Fry et al. (1960). For each cycle the cumulative record of responses was obtained. A straight line connecting the cumulative number of responses that occurred at second 3 to the cumulative number of responses at reinforcer availability was calculated. The area between the cumulative record and this straight line was then calculated. The curvature index was determined by dividing that area by the entire area under the straight line. The closer this area is to 1, the better the temporal discrimination.

3. Results

Fig. 2 shows the lever-press response gradients for the four groups (left panels) and the normalized gradients for the four groups (right panels), as a function of time since the last food. For the two fixed groups, the gradients increased as a function of time since the last food delivery, following a brief reaction to food (top left panel). The clearest difference between the two gradients was the rate: Group Signaled-Fixed (filled circles) showed a very low response rate, while Group Fixed (unfilled circles) ended the 60 s interval at about 30 responses per minute. The pattern of the two groups was similar: when the gradients were normalized such that the area under the curve was equal to one, they superposed (right top panel). The pattern was an approximately exponential rising function.

For the two random groups, the response rate was relatively flat throughout the 60-s interval (bottom left panel). Following food delivery there was an increase and decrease in the response gradient for the Random group, which can be attributed to response competition between the lever-press response and the head-entry response. Again, the clearest difference between the two groups is the difference in response rate. Group Signaled-Random (filled triangles) had a much lower response rate than Group Random (unfilled triangles) had a higher mean rate of response. The pattern of the two groups was similar: when the gradients were normalized such that the area under the curve was equal to one, they superposed (bottom right panel). The pattern was relatively flat.

In order to quantitatively compare the gradients, we separated the shape of the gradients (response pattern) from the height of the gradients (response rate). The mean rate across the 60-s interval was computed for each of the groups (top panel of Fig. 3). The shape of the gradients was compared using the curvature index (Fry et al., 1960) for the two fixed groups (bottom left panel), and a two-parameter straight line for the two random groups (bottom right panel).

A click at the time of food availability reduced response rates in both Groups Signaled-Fixed and Signaled-Random (top panel of Fig. 3). The presentation of a click resulted in significantly lower response rates than the absence of the click. The Fixed group responded significantly faster than the Signaled-Fixed group, with mean response rates of 5.95 and 0.85 responses per minute, respectively, $F_{1,10} = 17.04$, $p < .01$. The Random group responded significantly faster than the Signaled-Random group, with mean rates of 13.50 and 1.95 responses per minute, respectively, $F_{1,10} = 12.18$, $p < .01$. This difference in rate indicates that the presentation of a click at the time of reinforcer availability results in a much lower rate than if the food is not signaled.

The shape indices of the two fixed groups were not significantly different between the two fixed groups ($F_{1,10} = 0.86$, NS). The slopes for the individuals in the two random groups were close to zero, with little variability between rats but they did not approach a normal distribution so it was inappropriate to use an ANOVA on the data. These results show that, even though the response rates for the Signaled groups were lower than their unsignaled counterparts, the presentation of the click did not fundamentally alter the response pattern.
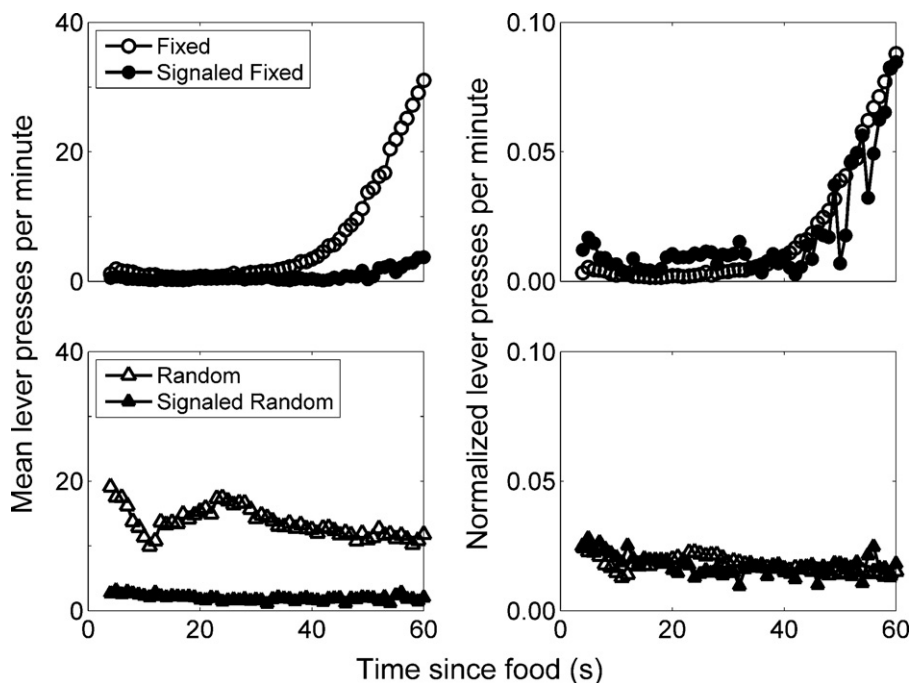

Fig. 2. The response gradients (left panels) and normalized response gradients (right panels) for the Fixed groups (top panels, circles) and the Random groups (bottom panels, triangles). The left panels show that the click at the time of food availability greatly reduced response rate; the right panels show that it did not have a large effect on overall response pattern.
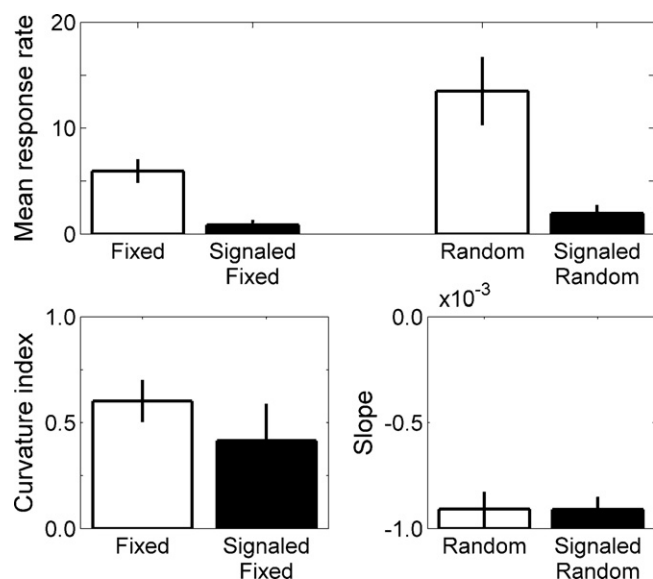
Fig. 3. Mean response rate (top panel) and response pattern measures (curvature index and slope of a straight line for bottom left and right panels, respectively) for the four groups. Response rate was significantly lower in the two signaled groups (top panel, black bars). The response pattern was not significantly affected by the signal in the groups with the same interreinforcer distribution (Fixed groups in the left panel, Random groups in the right panel).

4. Discussion

The empirical question was to determine whether a signal (e.g., a click) at food availability affects timing behavior of rats. In a simple between-groups design, one factor was whether or not a click occurred when the food was available. The results were very clear. The signal profoundly reduced the response rate, but there was no evidence that it had an effect on the response pattern.

The response pattern was determined by the interreinforcer-interval distribution. The two fixed groups had a similar characteristic ogival pattern that is observed following training on a fixed-interval schedule of reinforcement (Ferster and Skinner, 1957; Schneider, 1969), as indicated by the curvature index measure that was greater than zero. Not only were the curvature indices from the two groups not significantly different from each other, but the response gradients also superposed when plotted on a normalized scale. Similarly the two random groups had a characteristic flat rate of response that is observed following training on a random-interval schedule of reinforcement. The slopes of the gradients were not different from each other, and the gradients superposed when plotted on a normalized scale. These results were consistent with reports in the literature (e.g., Catania and Reynolds, 1968), as well as the predictions of models of timing (e.g., Guilhardi et al., 2007). Although the response rate was very low in the Signaled groups, the timing of their behavior was similar to that in the corresponding unsignaled groups.

At first glance this result may seem similar to that reported in the literature regarding signaled reinforcers. The effects of signaling reinforcement have been investigated using different schedules of reinforcement, including fixed-interval (Nakajima and Kitaguchi, 1996) and variable-interval schedules (Tarpy et al., 1984), differential reinforcement of low and high rates of response (Tarpy and Roberts, 1985), and ratio schedules (Reed et al., 1988). It has also been examined in different species including rats (e.g. Reed, 2003), pigeons (e.g., Mellon et al., 1995), and humans (e.g., Bradshaw et al., 1979).

The difference between those studies and the one reported here, is that the signal was usually presented only *after* the response

that delivered the reinforcer. Thus, it does not act as a second time marker independent of the response. Although the general consensus from the signaled reinforcement literature is that signaling the reinforcer results in a change in response rate, there have been many different interpretations as to *why* this occurs. These interpretations range from overshadowing to response potentiation (see Reed, 2003, for a summary of interpretations), but no unified theory is able to account for all of the patterns observed. This may in part be to the subtle but critical procedural difference of presenting the additional time marker either contingent on a response, or not contingent on a response.

In the procedure described here, a click was presented at the time of reinforcer availability, and was not contingent on a response. This click had a dramatic effect on the overall response rate, but no effect on the response pattern. The fact that response rate dropped to almost zero in a response-contingent lever-press press procedure when there was a signal just prior to food availability is a surprising result that cannot easily be explained using models of timing that do not incorporate information from multiple time markers (e.g., Gibbon et al., 1984; Machado, 1997).

The temporal location of the signal in this study was always presented at the time of reinforcer availability, i.e., there was no difference between the time of signal presentation and the time of reinforcer availability. There are theories that incorporate the idea of simultaneous temporal processing, such as Packet theory (Guilhardi et al., 2005). Packet theory is a quantitative theory of behavior that predicts both response pattern and rate. In Packet Theory, when more than one time marker is presented, the information from the time markers is combined using a linear averaging combination rule. Modular theory (Guilhardi et al., 2007) is a later revision of Packet Theory that is being extended to use the same linear averaging rule to combine temporal information from multiple time markers.

In a case such as the one presented here, almost all of the weight would be allocated to the time marker that best predicts food availability. In the Fixed and Random groups, the most effective time marker is the previous food delivery that occurred 60 s earlier. In the Signaled-Fixed and Signaled-Random groups, the most effective time marker is the click that is presented at the exact time of food availability.

Packet theory can be used to explain why the response patterns remained the same within the same type of schedule of reinforcement (i.e. Fixed or Random) even when the response rate was low. Because the two Signaled groups also had food delivery as a time marker, they timed the 60-s interreinforcer interval, in addition to the 0-s stimulus-to-reinforcer interval. Although they responded at a very low rate, there was still evidence that they tracked the 60-s interval, as shown in the normalized gradients. In addition, there was no difference between groups in the time from the lever press that delivered the food to the time of food retrieval, ($F_{3,20} = 0.51$, $p = 0.68$), with means of 0.53 (0.06), 0.52 (0.15), 0.37 (0.02), and 0.45 (0.12) for the Fixed, Signaled-Fixed, Random, and Signaled-Random groups, respectively (standard error shown in the parentheses). This would suggest that the rats timed the programmed schedule of reinforcement.

5. Conclusions

Although there has been extensive research that examines the relationship between the time of stimulus presentation and response rate, as well as the effect of multiple stimuli on response pattern, little, if any, research has been done on the effect of the presentation of a time marker at the time of reinforcer availability on both response rate and pattern. Previous research examining signaled reinforcement shows similar results, but is different in that the signal presentation itself is contingent upon a response. This

study showed that when a single stimulus was presented at the time of reinforcer availability, irrespective of the responses that the rat made, it reduces the response rates in rats to almost zero, but did not affect response pattern.

Acknowledgements

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