Timing in Choice Experiments

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Abstract

In Experiment 1, pigeons chose between variable- and fixed-interval schedules. The timer for 1 schedule was reset by a reinforcement on that schedule or on either schedule. In both cases, the pigeons timed reinforcement on each schedule from trial onset. The data further suggest that their behavior reflects 2 independent processes: 1 deciding when a response should be emitted and responsible for the timing of the overall activity, and the other determining what this response should be and responsible for the allocation of behavior between the 2 response keys. Results from Experiment 2, which studied choice between 2 fixed-interval schedules, support those 2 conclusions. These results have implications for the study of operant choice in general.

Timing and choice are major research topics in the field of animal learning (see Staddon & Cerutti, 2003; Williams, 1988, for reviews), but the two fields remain relatively isolated from each other. Nevertheless, procedures that explicitly relate choice and timing, such as the time-left procedure, have revealed the importance of temporal variables in choice (Cerutti & Staddon, 2004a; Preston, 1994; see Gibbon & Church, 1981, for historical justification of the time-left procedure). The present experiments continue this line of investigation.

Two basic choice procedures are concurrent schedules, which arrange choices between sources of primary reinforcers, and concurrent-chain schedules, which arrange choices between stimuli that signal the occurrence of primary reinforcers. Recently, Staddon and colleagues (e.g., Staddon & Ettinger, 1989; Staddon & Cerutti, 2003; see also Staddon, 2004, for an earlier account) have proposed that behavior seen in these procedures can be explained by timing principles: In a concurrent or concurrent-chain schedule, expected time to (primary) reinforcement on a schedule may determine when the subject starts responding (see Cerutti & Staddon, 2004b, for empirical evidence of timing in concurrent schedules). This temporal-differentiation view is able to account for a wide range of operant choice phenomena (Staddon & Cerutti, 2003; Staddon & Ettinger, 1989), but it leads to additional questions about the specific sources of temporal control.

Various events in a simple concurrent schedule, such as the onset of the two schedules (in a trial-based procedure) or reinforcement on one schedule or on the other (in a free-operant procedure), may serve as time markers that signal the upcoming time to reinforcement. In the more complex concurrent-chain procedure, the number of potential time markers is even larger. Each of these time markers may come to control operant responding in anticipation of the final primary reinforcer. If behavior in choice experiments is wholly or partly differentiated by

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temporal features of contingencies, then it is important to identify the controlling features: which events become effective time markers, and the specific interreinforcement intervals that contribute to response differentiation. The present experiments approach these questions by analyzing patterns of temporal differentiation under several versions of concurrent fixed-interval (FI) and variable-interval (VI) schedules.

Experiment 1

On interval schedules, a reinforcer is delivered for a response that occurs at least x s since a given time marker (e.g., the last reinforcement). In an FI schedule (Ferster & Skinner, 1957; Skinner, 1938), this interval x is fixed between trials, whereas in a VI schedule (Ferster & Skinner, 1957), it varies around a mean value between trials. Both of these arrangements produce distinctive patterns of temporally differentiated behavior: The FI schedule produces a scalloped pattern of responses, a pause after reinforcement followed by accelerated responding (Ferster & Skinner, 1957; Skinner, 1938); the VI schedule produces a short pause followed by a constant rate of responding (Ferster & Skinner, 1957).

Catania (1962) and Nevin (1971) have found that these patterns remain intact when FI and VI schedules are presented concurrently (two other studies of concurrent VI–FI schedules by Lobb & Davison, 1975, and Trevett, Davison, & Williams, 1972, failed to report the temporal pattern of responding on the two schedules), but they both used different stimuli during reinforcement to differentiate FI reinforcers from VI reinforcers, a procedure that is not standard with concurrent schedules. Will we find the same result without this modification?

In a concurrent schedule, a session may be divided into time periods or trials—each initiated and terminated by a reinforcer. The initiating reinforcer (trial onset) can be on the same schedule (produced by a response on the same side) as the second one (trial offset) or on a different one. We call *trial duration* the interval between two successive reinforcers, irrespective of whether the reinforcers are on the same schedule, and *interreinforcement time* the interval between two reinforcers on the same schedule.

Experiment 1 compares two versions of the concurrent FI–VI procedure, resetting and nonresetting. In the nonresetting procedure, the VI and FI timers continued to run from trial to trial (though not during the intertrial interval). This is the usual way to program a concurrent interval schedule (see, e.g., Catania, 1962; Nevin, 1971; Trevett et al., 1972). During the resetting procedure, both the VI and the FI timers began from zero at trial onset. In both cases, the FI interval and the average VI interval were 60 s. The VI was composed of 11 equally spaced intervals ranging from 35 s to 85 s (as in the original time-left experiment; see Cerutti & Staddon, 2004a).

The nonresetting procedure is described as a concurrent FI 60-s–VI 60-s schedule, because the scheduled interreinforcement time is approximately 60 s on the FI and, on the average, 60 s on the VI. Trial duration (as we have defined it) on both schedules is not directly controlled by the experimenter. The reverse is true for the resetting procedure. It is classified as a concurrent FI 60-s–VI 60-s schedule, because the trial duration is mostly 60 s on the FI and, on the average, 60 s on the VI. The interreinforcement interval (as we have defined it) on both schedules is not controlled in the resetting procedure.

In describing these two procedures, we change emphasis from the interreinforcement interval in the nonresetting procedure to the trial duration in the resetting one. Will the pigeons do the same? If they do, in the nonresetting procedure, their performance should be tuned to the interreinforcement intervals; in the resetting procedure, performance should be tuned to the trial durations. In the nonresetting procedure, their response rate on the VI should remain fairly constant as a consequence of the fairly uniform probability of reinforcement on that schedule,

whereas their response rate on the FI should increase as a function of the time elapsed since the last FI reinforcer. In the same way, in the resetting procedure, the response rate on the VI should be fairly constant, whereas the response rate on the FI should increase as a function of the time elapsed since trial onset. If the interval relevant to the birds (interreinforcement interval vs. trial duration) is the same in both procedures, the pigeons' performance in one of the two procedures, but not the other, should correspond to the description we have given. If only the nonresetting procedure gives the expected result, the pigeons are using the interreinforcement interval; otherwise, they are relying on the trial duration.

Method

Subjects—The subjects were 4 White Carneaux pigeons (2 males, Subjects 17267 and 6027; and 2 females, Subjects 2189 and 2087) maintained at 85% of their free-feeding weight. Three subjects had some experience with the apparatus. One of the 2 males but neither of the 2 females had served in experiments with FI schedules. Pigeons were housed in individual cages on a 12-hr light–dark cycle, with water available at all times.

Apparatus—A standard pigeon chamber (length 71.12 cm, width 53.34 cm, height 53.31 cm) was used. It was enclosed within a larger, sound-isolated box equipped with a ventilating fan. Walls and ceilings of the chamber were aluminum, except for the right and left walls, which were made of transparent Plexiglas. The floor was a standard wire grid.

On the front walls, three response keys (diameter 1.27 cm) were mounted 5.00 cm apart and centered 25.40 cm from the floor. Each key required a force of 0.7 N to operate. The center key was not used and remained dark during the whole experiment. The two side keys could be illuminated with white light. A grain hopper mounted in the center of the front wall, 8.89 cm from the floor, provided reinforcement. The hopper was illuminated when a reinforcer was available. General illumination was provided by a houselight in the center of the ceiling. A peephole in the right wall of the wooden box allowed the experimenter to observe the pigeon during a session without being noticed. Experimental procedures were controlled, and data were recorded by a computer close to the chamber.

Pretraining—We obtained initial pecking on both keys by illuminating one of the two keys and reinforcing the first peck to it with 7-s access to food; which key was illuminated was determined randomly after each reinforcer. During reinforcement, both keys were dark and the houselight was off. This training ended when we observed that the pigeon reliably pecked at the illuminated key.

In the next training phase, the two keys were simultaneously illuminated by white light, and pecks to each key were reinforced on a concurrent random-interval (RI) 10-s schedule. An RI schedule is a variant of a VI schedule: The probability of reinforcement is constant from moment to moment, and, hence, the average interval between two successive reinforcers is controlled. The reinforcer was 2-s access to food. Again, the keys were dark and the houselight was off during reinforcement. To obtain pecking on both keys, a Shull–Pliskoff (1967) procedure was used: If a reinforcer was scheduled on one of the keys, the clock scheduling reinforcement for the other key stopped until this reinforcer had been collected. A session ended after 50 reinforcers had been collected. Once the pigeons began to respond equally to each key, the experiment, proper, began.

Procedure—The subjects were exposed to a concurrent VI 60-s–FI 60-s schedule. The initial position (left vs. right key) of the FI was counterbalanced among pigeons. Daily experimental sessions terminated when a pigeon had collected 50 reinforcers. A trial began with the illumination of left and right keys. Responding on one key was reinforced on an FI 60-s

schedule; responding on the other key was reinforced on a VI 60-s schedule. In each case, the reinforcer was a 2-s access to food. During reinforcement, the two keys were darkened and the houselight was off. The VI schedule was composed of 11 intervals (35 s, 40 s, 45 s, 50 s, 55 s, 60 s, 65 s, 70 s, 75 s, 80 s, and 85 s) corresponding to the values used by Gibbon and Church (1981; in one of their conditions) and by Cerutti and Staddon (2004a). The collection of a reinforcer terminated a trial. Separating trials was a 15-s intertrial interval during which the chamber was darkened.

There were two conditions. In the nonresetting procedure, the VI and FI timers continued to operate from trial to trial (though not during the intertrial interval). During the resetting procedure, the VI and FI timers began from zero at trial onset. Two pigeons (Subjects 2087 and 2189) experienced the resetting procedure first. Because of the relocation of our laboratory facilities halfway through procedures, Subject 6027 was only exposed to the nonresetting procedure.

The raw dependent variable was the absolute time (recorded to the nearest 0.05 s) of all experimental events: key pecks, stimulus changes, and reinforcer deliveries. Conditions—resetting or nonresetting—lasted for a minimum of eight sessions and were changed if the pattern (mean proportion of responses, in 5-s bins) on the FI during a trial had been stable for the last three sessions. The positions of the VI and FI keys were alternated according to an A–B–A–B series. The experiment was terminated once successive A (respectively, B) treatments were similar: Each pigeon experienced at least four conditions, more if this stability criterion was not met. Only the data from the four last replications are reported.

Results

Figure 1 shows mean response rates on FI and VI schedules in the nonresetting procedure, plotted as a function of time in trial. We computed the mean response rates by averaging each pigeon's data from the last three sessions in each reversal condition and then averaging all the pigeons. Because there was no detectable effect of the location of the two schedules (left key vs. right key) and both the intrasubject and intersubject variability were small, these curves are representative of the individual performances. The data in Figure 1 show no preference whatsoever for either schedule: The two curves overlap, indicating that the proportion of responding on each key remained around 50% during a trial.

Figure 2 shows the response rates on FI and VI schedules in the resetting procedure as a function of the time since the beginning of a trial. Because there was an effect of the left–right location of the schedules, data for each schedule arrangement are presented separately. Because there were two conditions for each schedule arrangement, each plot is the mean of the last three sessions before a reversal in both replications. Response rate on both schedules changed in a different fashion as a function of trial time: It increased on the FI as time elapsed but changed in a bitonic pattern on the VI. During the initial part of a trial, when response rate on both schedules was increasing, it always increased faster on one schedule than on the other. We label this schedule the preferred side, as the preference seemed to be related more to the location of the schedule (left vs. right key) than to the nature of the schedule per se (VI vs. FI). Hence, the preferred side switched to the FI from the VI and vice versa as the positions were switched from the left key to the right key.

An interesting regularity in overall response rates on the resetting procedure is shown in Figure 3. This figure shows that the overall response rate (responses per second, no matter on which schedule they were emitted) remained roughly the same from one condition to the other (i.e., reversals in the left–right arrangements of FI and VI schedules), increasing during a trial according to an S-shaped function. Note that this pattern in overall rate, which we obtained simply by summing the two curves in each individual panel of Figure 2, emerged despite large

individual differences in response allocation to each schedule between reversals in schedule arrangements (due to whether the FI was on the preferred side).

Discussion

Behavior in the nonresetting procedure (see Figure 1) is comprehensible if we assume that pigeons time reinforcement from trial onset. Figure 4 shows that the distributions of times to reinforcement, timed from trial onset, were very similar on both schedules (as well as extremely variable across sessions). If time to reinforcement controls the pigeon's behavior, we should expect identical response patterns on each schedule. Both the VI and the FI time-to-reinforcement distributions are VI-like, as seen in Figure 1, and the way response rate increased as a function of time since trial onset resembles the pattern on VI schedules (Catania & Reynolds, 1968;Lund, 1976).

This is consistent with a study by White and Davison (1973), who exposed pigeons to various concurrent FI schedules. With some schedule pairs (e.g., a concurrent FI 130-s–FI 120-s schedule), they observed VI-typical behavior (no pausing; constant rate of responding) on both schedules, whereas on others (e.g., a FI 25-s–FI 120-s schedule), they observed FI-typical performance (scallop; a pause followed by an accelerating rate of responding) on the schedule with shorter interval and VI-like behavior on the other. Both outcomes should be expected if pigeons time reinforcement from trial onset (although one result, White & Davison's, 1973, observation of FI-like behavior on both schedules in a concurrent FI 36-s–FI 48-s schedule, remains puzzling).

However, this interpretation appears to conflict with the results of Catania (1962) and Nevin (1971), who, in a concurrent VI–FI, found VI-typical performance on the VI and FI-typical performance on the FI, an outcome that seems to indicate a control by the interreinforcement interval rather than by trial duration. Although no stimulus-control tests were done, it seems probable that the result was due to the use of differential stimuli to discriminate between FI and VI reinforcers, although there were several other differences between the authors' procedures and the one used here. For instance, to further differentiate the two schedules, Catania (1962) used different colors for the two response keys. Another difference is that we used no change-over delay, which might have led to switching behavior that made separation of the two schedules more difficult. Indeed, Catania (1962) observed that, in a concurrent VI 3-min–FI 6-min schedule, the performance was VI-like on both schedules if a change-over delay was not used, a result that he attributed to the reinforcement of switching behavior.

As Table 1 shows, when performance was stable in the resetting procedure, almost all reinforcers were collected on the FI. The reason is straightforward. Suppose that the scheduled interval on the VI is longer than 60 s, perhaps $60 + x$ s. Under these conditions, the pigeon has x s to collect the reinforcer on the FI. Hence, even if the probability of responding on the FI is low at that point, an FI reinforcer is bound to be collected sometimes. Because the VI interval is not changed when a reinforcer is collected on the FI, this starts a chain of events that should lead to a strong preference for the FI around 60 s in a trial: The probability of responding on the FI is increased, which enhances the likelihood that it collects an FI reinforcer during the x-s interval, which increases the probability of responding on the FI, and so forth.

Therefore, the mean time to reinforcement in the resetting procedure is 60 s, because most of the reinforcers were collected on the FI (see Table 1); this, from the point of view of the time-to-reinforcement distribution, makes this procedure similar to an FI. In a review of research covering several species, Lejeune and Wearden (1991) concluded that the pattern of response rate in an FI follows an S-shaped function, well fit by a Gaussian function (see also Killeen, Hanson, & Osborne, 1978;Lund, 1976). Data from the peak procedure (Catania, 1970;S. Roberts, 1981;W. A. Roberts, Cheng, & Cohen, 1989) point toward the same conclusion.

Hence, the overall response rate in this concurrent FI–VI schedule (see Figure 3) changes in the same way during a trial as does response rate in a simple FI schedule. This, combined with the fact that this pattern is not affected by the position of the FI (right vs. left key; see Figure 3)—even though this variable has a major impact on the allocation of responding on the two keys (see Figure 2)—suggests that the behavior of the pigeons is the result of the interaction between two independent processes: The first one, the timing process, determines when a response should be emitted; the second one, the response allocation process, determines what that response should be.

The timing process is influenced mainly by the time-to-reinforcement distribution and controls the temporal pattern of the overall (left + right) response rate. The Pavlovian nature of this process is suggested by other results in the literature. For example, Wynne and Staddon (1988) studied pigeons in a schedule in which food was delivered a fixed amount of time after the pigeon's first peck on a key (a response-initiated delay schedule). This procedure should reinforce short postreinforcement pauses because they lead to smaller interreinforcement times and higher reinforcement rate. However, Wynne and Staddon (1988) found that the duration of the pause was a function of the last interreinforcement interval. They concluded that the pause was not an operant activity: It was obligatory, determined primarily by the duration of the interreinforcement interval. In another study, Baum (1993) studied pigeons in yoked VI variable-ratio (a variable number of responses must be emitted for a response to be reinforced) schedules and found that the duration of the pause for a given pigeon in the two schedules was the same if the reinforcement rate was equated. Baum (1993) concluded that pausing was a respondent process controlled mainly by the reinforcement rate. These results may be related to research showing the development of schedule-induced interim behavior on response-independent schedules of reinforcement (e.g., Brown & Jenkins, 1968; Staddon & Simmelhag, 1971; see Staddon, 1977, for a review).

In contrast, the response allocation process seems to be operant—that is, sensitive to the response-reinforcer contingencies—although other variables, such as side bias, can also influence it. The impact of a response-reinforcer contingency on this second process is a function of the time to reinforcement for that response. At the beginning of a trial, the FI 60-s reinforcer is too delayed to have a major impact on response allocation, so side bias is the main influence: The pigeons respond mainly on the side toward which they are biased, regardless of the schedule on it. Later in a trial, when time to the FI 60-s reinforcer is reduced, the response allocation process is mainly influenced by it, and the pigeons respond mainly on the FI, no matter what its location. Because the rate of reinforcement on the VI is almost nil, it is unlikely that the response-reinforcer contingency on that schedule has any influence on the response allocation process. Hence, the patterns observed in Figure 2 are the results of the interaction among the timing of the overall activity (see Figure 3), the growing influence of the FI 60-s reinforcer on the response allocation process as time to reinforcement on the FI decreases, and response competition: As the probability of responding on the FI increases, the probability of responding on the VI jointly decreases.

Church, Lacourse, and Crystal (1998) studied the temporal pattern of response rate in rats exposed to a concurrent FI 60-s–VI 60-s schedule in which, just as in our resetting procedure, reinforcement was timed by the experimenter via trial duration rather than the interreinforcement interval (as in typical concurrent schedules). At the beginning of each trial, a reinforcer was randomly scheduled either on the FI 60-s or the VI 60-s schedule. The authors compared the rats' performance in this situation with their behavior in a task in which they had been exposed only to either the FI 60-s or the VI 60-s schedule. They found that the temporal pattern of response rate in the concurrent schedule matched the patterns observed in the simple schedules. The conclusions from the resetting procedure might lead us to conclude the opposite, but the many differences between Church et al.'s (1998) procedure and ours preclude any

definitive account. Besides possible interspecies differences between rats and pigeons, Church et al.'s (1998) VI was different from ours (a uniform distribution of intervals between 1 s and 121 s). Moreover, the fact that the rats were preexposed to one of the simple schedules before being exposed to the concurrent one could also be important. Finally, the authors reported only group data for the concurrent schedules: If their rats displayed the same variability as the one observed in the pigeons (see Figure 2), it would be difficult to draw definitive conclusions from the average curves.

Experiment 2

The results of Experiment 1 suggest an interesting generalization. In traditional operant theories (see, e.g., Williams, 1988), response rate on one schedule is supposed to be mainly determined by the reinforcement rate on that schedule. (This is the basis for the matching law, which states that, in a concurrent schedule, relative response rates match relative reinforcement rates. See Herrnstein, 1961, and Williams, 1988, for further details.) Reinforcement rate is, of course, the reciprocal of the average interreinforcement time on that schedule for a given time period. Using reinforcement rate as an independent variable implicitly assumes that the relevant time interval for the animal is interreinforcement time—that is, the time between two successive reinforcers on the same side. However, the nonresetting procedure (see Figure 1) suggests that trial duration (the time between two reinforcers) may sometimes be the relevant interval.

The goal of Experiment 2 is to examine the relative importance of trial duration and interreinforcement time in a more direct way. We exposed the pigeons to the modified concurrent FI–FI schedule shown in Figure 5: Reinforcement on one key was scheduled at 20 s in a trial if the previous reinforcer had been collected on the second key, whereas reinforcement on the other key was scheduled at 60 s in a trial if the previous reinforcer had been collected on the first key. A 15-s intertrial interval followed every reinforcement. This arrangement ensured that trial duration was 20 s on the first key and 60 s on the second key, whereas the interreinforcement time was the same, 95 s (20 s + 60 s + 15 s), on both schedules. Defined in terms of trial duration, the first key is an FI 20-s schedule, and the second key is an FI 60-s schedule. If trial duration is the critical determining variable in a concurrent schedule, we should observe a pause on both schedules after each reinforcer. Moreover, the pigeon should prefer the FI 20-s schedule early in a trial, switching to the FI 60-s schedule later. Conversely, if interreinforcement time is the controlling variable, because it is equal to 95 s on both schedules, the pigeon should pause only on the schedule for which it has just been reinforced. Hence, it should prefer the FI 60-s schedule after an FI 20-s reinforcer (because it pauses only on the FI 20-s schedule) and the FI 20-s schedule after an FI 60-s reinforcer.

Note that if trial duration is the relevant interval for the pigeon, then this concurrent schedule should be similar (from the pigeon's point of view) to a single-key mixed FI 20-s–FI 60-s schedule. Hence, according to the theory proposed in the discussion of Experiment 1, the temporal pattern of the overall response rate in the concurrent FI–FI schedule should be similar to the temporal pattern of response rate in the mixed schedule. This is a critical prediction, which we test in this experiment by also exposing the pigeons to a mixed FI 20-s–FI 60-s schedule.

Method

Subjects and apparatus—The subjects were 7 White Carneaux pigeons (5 males, Subjects 17267, 1239, 17201, 7227, 4157, and 1853; and 1 female, Subject 2087), maintained at 85% of their free-feeding weight. All had some experience with the present apparatus, and all but 2 (Subjects 1239 and 4157) had been used in timing experiments. Housing and care were as in Experiment 1. Experimental chambers were those used in Experiment 1.

Procedure—Before starting the experimental procedures, the pigeons were trained as in Experiment 1. After training, 4 subjects (Subjects 17267, 1239, 17201, and 2087) were exposed to the modified concurrent FI–FI schedule shown in Figure 5. The initial position (left vs. right key) of the two FI schedules was counterbalanced among pigeons. Daily experimental sessions terminated when a pigeon had collected 50 reinforcers. A trial began with the white illumination of left and right keys. Reinforcement on one key (the FI 20-s key) was scheduled at 20 s in a trial if the previous reinforcer had been collected on the other key, whereas reinforcement on the other key (termed the FI 60-s key) was scheduled at 60 s in a trial if the previous reinforcer had been collected on the FI 20-s key. Hence, reinforcers on both keys alternated, with an FI 20-s reinforcer always being followed by an FI 60-s reinforcer. Both keys were white throughout, except during reinforcement and during the 15-s intertrial interval that followed reinforcement. The houselight was also off during these two events.

In addition to the concurrent schedule illustrated in Figure 5, these 4 pigeons were also exposed to a single-key mixed FI 60-s–FI 20-s schedule. The procedure was similar to the one used for the concurrent schedule, except that the two side keys were darkened and the center key was illuminated white. Responding on that key was reinforced according to an FI 60-s schedule or an FI 20-s schedule. The two schedules alternated, so that, after the FI 60-s schedule was active, responding was reinforced according to an FI 20-s schedule, and so on. As in the concurrent FI–FI condition, trials during a session were separated by a 15-s blackout, and a session always began with an FI 60-s interval. Two pigeons (Subjects 2087 and 17267) were exposed to the mixed schedule before the concurrent one, whereas the other pigeons (Subjects 1239 and 17267) experienced them in the reverse order.

To assess the impact of the 15-s intertrial interval on the subjects' performance, we exposed the 3 remaining pigeons (Subjects 7227, 4157, and 1853) to a replication of the concurrent FI–FI schedule. The procedure was exactly the same as the one described above, except that the 15-s intertrial interval was omitted. A new trial began just after a reinforcer has been collected; as a consequence, the interreinforcement time was 80 s.

The raw dependent variable was the absolute time (recorded to the nearest 0.05 s) of all experimental events: key pecks, stimulus changes, and reinforcer deliveries. The left–right position of the FI 20-s schedule in the concurrent schedule was alternated according to an A–B–A–B series. Just like in Experiment 1, the concurrent schedule condition was terminated once the performances in two A (respectively, B) treatments were similar. Only data from those last four replications are reported. A reversal of the position of the FI 20-s schedule took place after a minimum of eight sessions if the pattern of the proportion of responding on the FI 20-s schedule had been stable for the last three sessions. The mixed schedule condition was terminated once the temporal pattern of response rate during a trial had been similar during the last three sessions and the pigeon had been exposed to a minimum of eight sessions.

Results

On the concurrent schedule, the pigeons showed some side bias, but less than in the resetting procedure in Experiment 1. The pattern of response rate stayed roughly similar, no matter the position of the schedules, and dramatic changes in performance such as those displayed in Figure 2 were not observed. Therefore, we do not present separately conditions in which the FI 20-s schedule was on the left and right: Each plot in Figures 6, 7, 8, and 9 is the mean of the last three sessions before a reversal for all four replications in the A–B–A–B series.

Figure 6 shows the proportion of responding on the FI 20-s schedule, and Figure 7 shows the pattern of response rate on both schedules, both as a function of the time elapsed since trial onset. Both figures tell the same story: Each pigeon started responding on the FI 20-s schedule early in every trial before switching to the FI 60-s schedule later. The same pattern was observed

both in 20-s trials (on which reinforcement was scheduled on the FI 20-s schedule) and 60-s trials (on which reinforcement was scheduled on the FI 60-s schedule). Although response rate was higher in 20-s trials (see Figure 7), the proportion of responding on the FI 20-s schedule was similar in both kinds of trials (see Figure 6). Figure 8 shows that these conclusions also apply to the pigeons exposed to a replication of the concurrent FI–FI procedure without the 15-s intertrial interval, although the response rate difference between the 20-s trials and the 60-s trials was smaller.

Figure 9 compares the pattern of response rate in the mixed schedule with the pattern of overall response rate in the concurrent schedule. The data for the mixed schedule are the means of the last three sessions in that condition, whereas the data for the concurrent schedule correspond to the data displayed in Figures 6 and 7. The trial duration distribution was the same in the concurrent and mixed schedules, with peaks around 20 s and 60 s. As in the resetting procedure (see Figure 3), there was no significant difference in the pattern of the overall response rate as a function of the position of the schedules (see the standard deviation in Figure 6), which, in this case, is not surprising, because, as we pointed out earlier, the side bias had only a minor effect on the allocation of behavior between the two keys. As seen in Figure 9, there were important individual differences in the way response rate in the mixed schedule and overall response rate in the concurrent schedule changed across trial time, but, for a given subject, response rate differed in the two conditions only in absolute value: The response rate was higher in the mixed schedule for Subjects 2087 and 1239 and lower for Subjects 17201 and 17267. The across-conditions pattern was similar for all birds.

The tracking (response rate higher in 20-s trials) displayed in Figure 7 is, of course, also observed in the pattern of the overall response rate in Figure 9, and 2 subjects (Subjects 2087 and 1239) displayed it also in the mixed schedule: As in Figure 7, although response rate was higher in 20-s trials, its temporal pattern was the same in both kinds of trials.

Discussion

The temporal pattern of response proportion and response rate in Figures 6 and 7 clearly shows that the pigeons' behavior was under the control of trial duration. They were timing reinforcement from trial onset and reacted to the alternating schedule as if it were a concurrent FI 20-s–FI 60-s schedule rather than a concurrent FI 95-s–FI 95-s schedule. Although the use of an intertrial interval might have favored the selection of trial onset as a time marker (by making it more salient or by weakening the effect of the previous reinforcer on the same schedule), the same results were obtained in a replication that lacked the 15-s intertrial interval (see Figure 8), which suggests that the intertrial interval was not critical to control of responding by trial time. Although the generality of those conclusions needs to be tested more extensively, this study raises the possibility that, on many standard concurrent procedures, behavior might be controlled by time since trial onset rather than by interreinforcement time on the separate schedules, as is usually assumed.

In the discussion of Experiment 1, we proposed that the pattern of overall response rate in a concurrent schedule, and response rate in a simple schedule, is determined by a timing process influenced in a Pavlovian way by the time between two reinforcers—that is, by the trial duration. In other words, our suggestion is that the time-in-trial distribution of reinforcement determines $p(t)$, the probability of emitting a response t units of time in a trial. Of course, we cannot measure this probability directly, and we use instead as an estimate $p'(t)$, the mean probability of responding during the interval $(t - T/2, t + T/2)$, with

$$p'(t) = \int_{t-\frac{T}{2}}^{t+\frac{T}{2}} p(t)dt,$$

where T is the duration of the time window used in our estimate—for example, 5 s in our experiment. During the interval $(t - T/2, t + T/2)$, the probability of responding is sampled a times at a mean rate $p'(t)$ to generate $ap'(t)$, the response rate during interval $(t - T/2, t + T/2)$.

This rate of sampling a is a function of several variables (including, probably, motivational ones), and, if it is changing, the absolute value of response rate at time t also changes even though the underlying probability $p(t)$ and its mean estimate $p'(t)$ remain constant. Therefore, variations in the absolute value of the response rate between the concurrent and the mixed schedule are not important for our model. Its predictions concern the invariance of the underlying probability of responding, which is reflected in the shape of the pattern of response rate during a trial.

Hence, the data in Figure 9 clearly support our hypothesis about two independent processes, although alternative interpretations are possible. Some theorists (Catania & Reynolds, 1968; Machado, 1997) have proposed that performance in a mixed schedule is the sum of the performances induced by the individual FI schedules composing it. In our case, the pigeons' performance in the mixed FI 20-s–FI 60-s schedule is the sum of the performances observed on the FI 20-s and FI 60-s schedules. The concurrent schedule separates these two components of mixed schedule performance, making the FI 20-s schedule part and the FI 60-s schedule part explicit by linking them to different response keys. That could explain the invariance of the pattern of response rate in the two schedules observed in Figure 6. Two facts argue against this interpretation in favor of our original hypothesis. First, contrary to the other pigeons, Subject 17267's behavior in the concurrent schedule cannot be considered as a typical performance on the FI 20-s schedule along with a typical performance on the FI 60-s schedule. Despite this fact, this subject's overall response rate in the concurrent schedule still changed in the same way during a trial as its response rate in the mixed schedule. Second, this alternative explanation cannot account for the invariance of the overall response rate in the resetting procedure (see Figure 3), whereas our hypothesis accounts for the data of both Experiments 1 and 2.

In Experiment 2, an FI 20-s reinforcer was always followed by an FI 60-s reinforcer, and vice versa. The increased response rate in 20-s trials (Figures 7 and 9) shows that the pigeons learned this regularity in some way. The fact that the proportion of responding on the FI 20-s schedule was the same no matter the current time to reinforcement (see Figure 6), even though this variable affected the value of the absolute response rate, indicates that this tracking behavior was due to a modification of the sampling rate (see above) of the underlying probability of responding, not to a change in that underlying probability.

The tracking behavior observed in our experiment does not correspond to the temporal tracking usually reported in the literature. Most studies on tracking (e.g., Higa, Wynne, & Staddon, 1991) have reported that pigeons adjust their pause to match the last interreinforcement interval experienced. In the case of our experiment, that would lead the pigeons to display a shorter pause (and/or a higher response rate) after an FI 20-s reinforcer and a longer one (and/or a lower response rate) after an FI 60-s reinforcer. They actually displayed the reverse pattern: Instead of reacting to the just-experienced interreinforcement interval, they seemed to anticipate the current time to reinforcement.

Ludvig and Staddon (2004, in press) have studied tracking behavior in pigeons in various schedules, including simple mixed schedules with only two intervals, which alternated just as

in our experiment. In most of them (mixed FI 30-s–FI 90-s, mixed FI 60-s–FI 180-s, mixed FI 30-s–FI 180-s schedules), they observed either no tracking (the duration of the pause was the same no matter the current time to reinforcement) or one-back tracking (the duration of the pause matched the last experienced time to reinforcement). Anticipatory tracking (the duration of the pause matches the current time to reinforcement), like that observed in Experiment 2, developed only in two conditions, both of which used a very short FI 5-s schedule as a component of the mixed schedule (mixed FI 5-s–FI 30-s schedule, mixed FI 5-s–FI 180-s schedule).

It is, in some sense, puzzling that, although variation in absolute response rate clearly indicates that the pigeons discriminate between the 20-s and the 60-s trials and their response allocation between the two keys shows that they know approximately when food is available on which schedule, they nevertheless do not combine these two bits of information to respond only on the FI 20-s schedule during a 20-s trial and only on the FI 60-s schedule during a 60-s trial. This is the same kind of irrational behavior that can be observed in other instances of animal behavior, such as when gerbils and ants head back to their nests relying only on dead reckoning and ignoring obvious clues originating from the nest or from nearby landmarks (e.g., Mittelstaedt & Mittelstaedt, 1982). As in the case of spatial navigation, puzzling contradictions such as this are consistent with the idea that the behavior is determined by several independent processes using different environmental information as their input.

General Discussion

These experiments study the behavior of pigeons in choice situations with an important temporal component. We have found two new things. First, the indifference between the VI and the FI in the nonresetting procedure (see Figure 1), along with the pattern of responding observed in the concurrent FI 20-s–FI 60-s schedule (Figures 6, 7 and 8), shows that in our concurrent schedules, pigeons timed reinforcement from trial onset and that trial duration, not interreinforcement time, was the relevant interval. The subjects timed reinforcement not from the previous reinforcement obtained by a response on that side but from the previous reinforcement obtained by a response on either side. This conclusion contradicts the usual assumption that choice behavior on concurrent schedules is controlled by the distribution of interreinforcement times associated with each choice. The Catania (1962) and Nevin (1971) studies discussed previously show that pigeons' behavior in a concurrent schedule can be controlled by the interreinforcement time, but further research is needed to investigate the conditions necessary for each choice response to come exclusively under the control of reinforcements produced by that response. What is now clear is that such conditions did not exist in our experiments.

Because pigeons' behavior in standard concurrent interval schedules conforms to the matching law, a result that assumes control by interreinforcement time, it seems, at first glance, unlikely that our conclusions can be generalized to those schedules. However, it is interesting to note that a model developed by Cerutti (in press) is able to produce undermatching and preference for a VI over an FI schedule, even though it is timing reinforcement from trial onset, as our results assume. A possible explanation for matching even when choice responses are controlled by trial time rather than interreinforcement interval is that the interreinforcement-interval distribution and the trial duration distributions are correlated. In this case, the average choices of an animal based on one are very similar to its choices based on the other. Figure 10 provides some support for this idea. It shows the two steady-state distributions in a concurrent RI 15-s–RI 45-s schedule. (See Cerutti & Staddon, 2004b, Experiment 3, for further details on the procedure. Figure 10 is based on an average of the 3 pigeons used in that experiment. This average is representative of the individual findings.) The two distributions are indeed very similar. The main difference is that the short (RI 15-s) and long (RI 45-s) trial duration

distributions are more similar to each other than are the two interreinforcement time distributions. Thus, if subjects in these procedures are indeed responding according to the trial duration distributions rather than interreinforcement time distributions, they might be expected to show undermatching, which is, in fact, a frequent result (Baum, 1979). Our data by no means prove that pigeons time reinforcement from trial onset in standard concurrent schedules, but they do raise this as a serious possibility that requires additional testing. Perhaps this line of analysis can lead to a better understanding of performance in concurrent schedules by explaining not only matching but systematic deviations from it, such as under- and overmatching.

Our second finding is that the insensitivity of the temporal pattern of the overall response rate to the reversal of the position of the schedules (see Figure 3) in the resetting procedure, along with the invariance of the dynamics of response rate and overall response rate in the mixed and concurrent FI 20-s–FI 60-s schedules (see Figure 9), suggests that two independent processes, a timing process and a response-allocation process, underlie the pigeons' performance. The timing process determines when a response should be emitted and is controlled in a Pavlovian way by the trial duration distribution. The allocation process determines what this response should be and is influenced by the response-reinforcer contingencies and some other variables, such as side bias. A third sampling process is suggested by the data from Figures 6, 7, and 9, which show that the temporal pattern of responding as well as the allocation of behavior on the two schedules remain invariant despite differences in the absolute response rate.

Recent theoretical work (e.g., Staddon & Cerutti, 2003; Staddon & Ettinger, 1989) has argued for the integration of timing principles into the theoretical analysis of choice. The present results (see also Cerutti & Staddon, 2004b, for a related approach to concurrent chained schedules) suggest that this approach may lead to new insights in our understanding of concurrent schedule performance in general.

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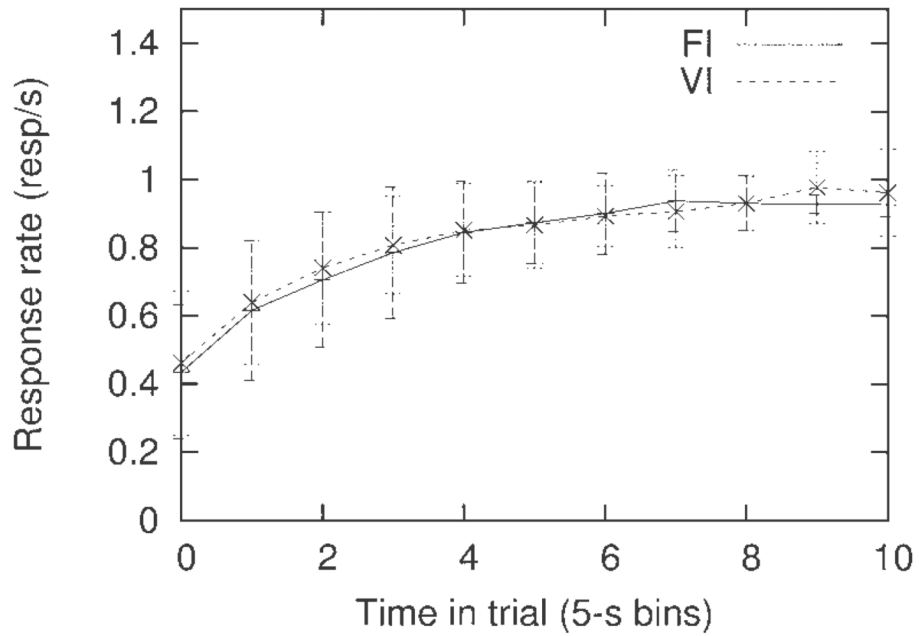
Figure 1.
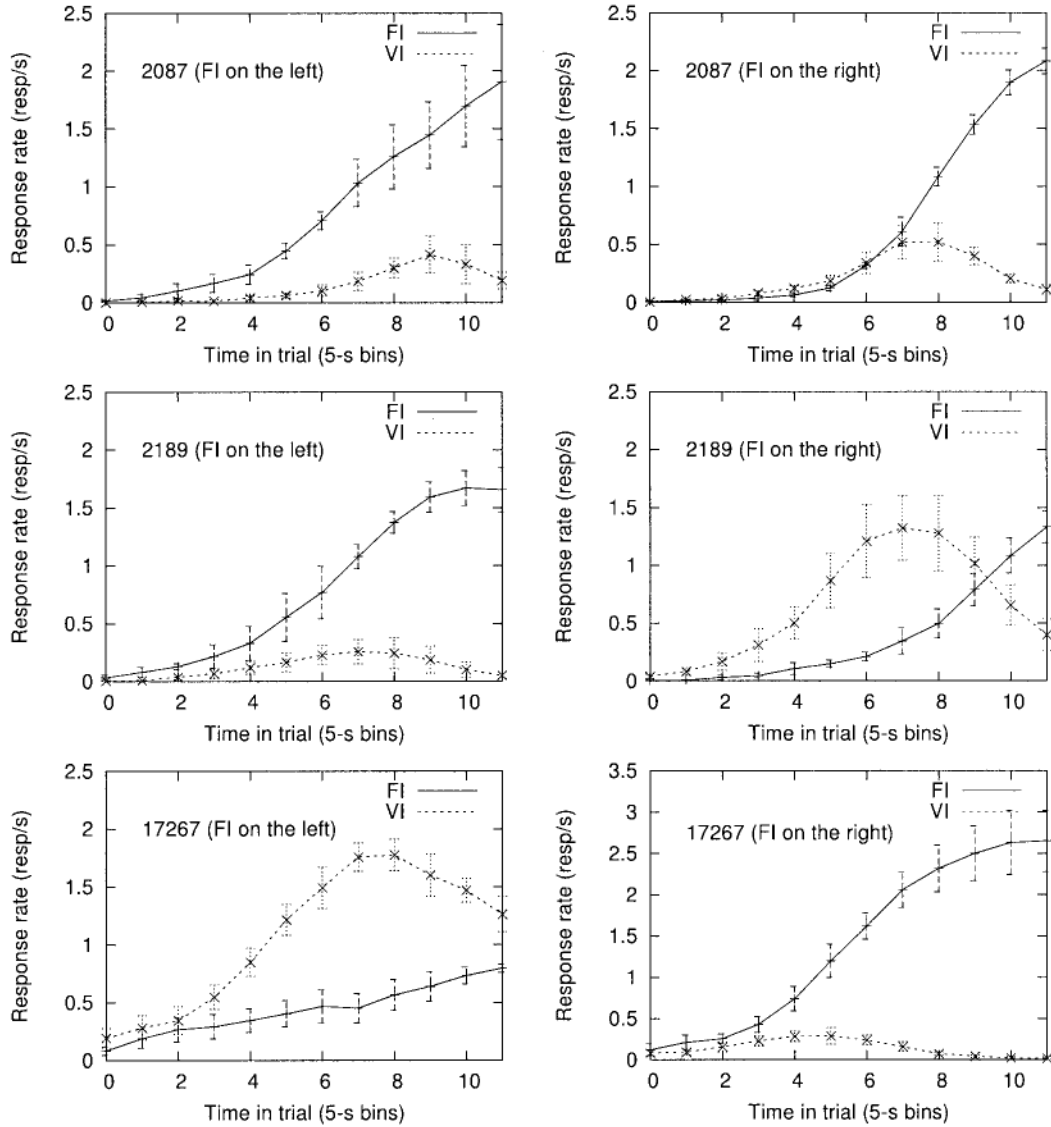Mean response rate on VI (dashed line) and FI (solid line) schedules in the nonresetting procedure of Experiment 1. Rates are shown as a function of the time since the beginning of a trial, partitioned in 5-s bins. Data are averaged over conditions and pigeons; error bars are standard deviations. resp/s = responses per second; FI = fixed interval; VI = variable interval.
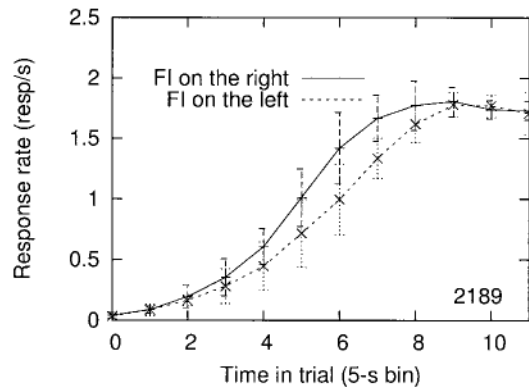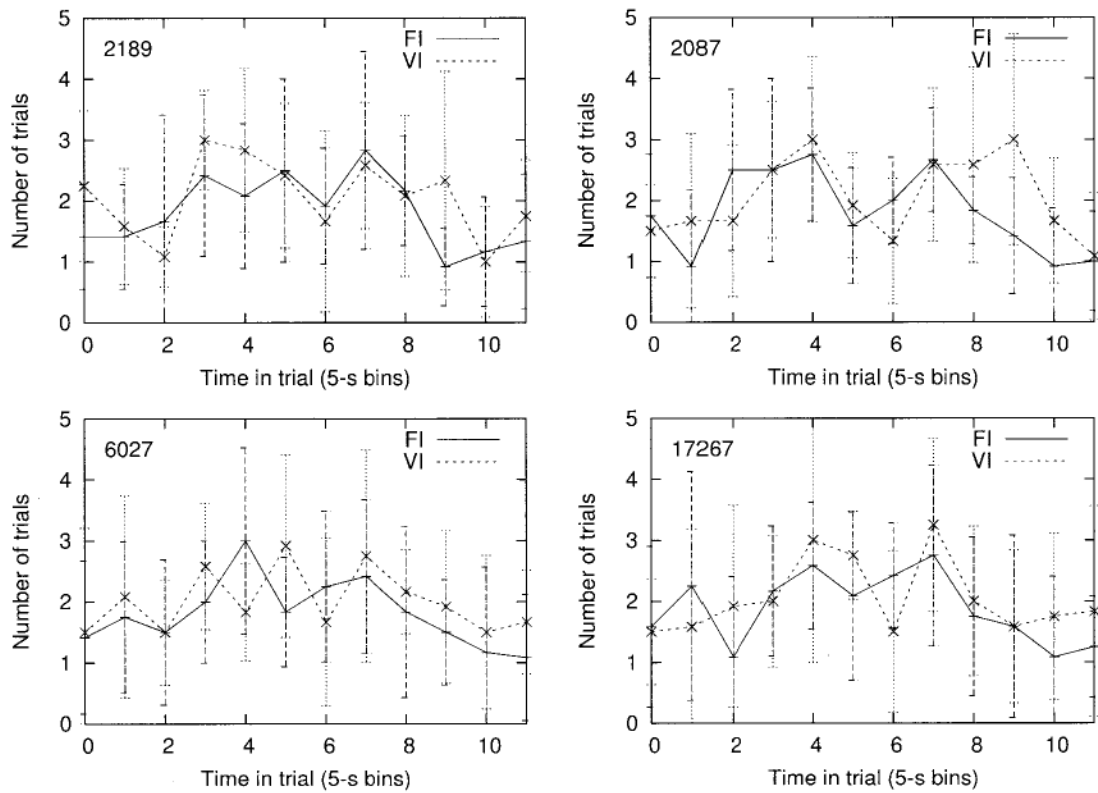
Figure 2.
Response rate on VI (dashed line) and FI (solid line) schedules in the resetting procedure of Experiment 1, plotted in 5-s bins as a function of time in trial. Left plots show performances with the FI on the left key; right plots show performances with the FI on the right key. Data are averaged over conditions and pigeons; error bars are standard deviations. resp/s = responses per second; FI = fixed interval; VI = variable interval.
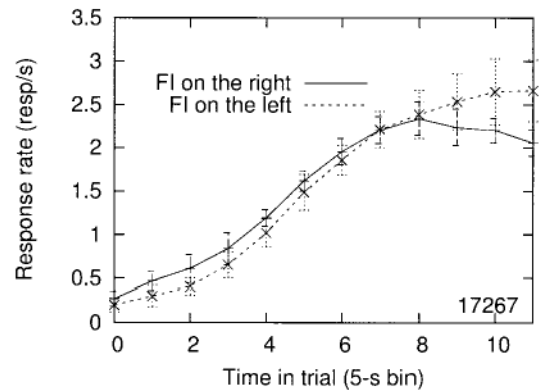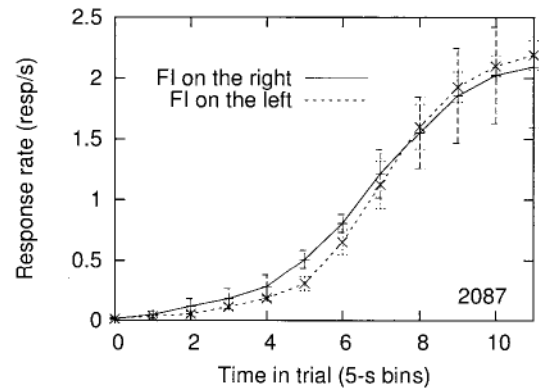
Figure 3.
Overall response rate in the resetting condition of Experiment 1 as a function of schedule arrangement (side of the FI) and time since the beginning of a trial for each pigeon. Data are averaged over conditions and pigeons, as in Figure 2; error bars are standard deviations. resp/s = responses per second; FI = fixed interval; VI = variable interval.

Figure 4.
Distribution of time to reinforcement (latency of reinforcement timed from the beginning of the trial) in the nonresetting procedure of Experiment 1. FI data are shown with solid lines; VI data are shown with dashed lines. Data are averages from the last three sessions before a reversal, averaged over reversals; error bars are standard deviations. FI = fixed interval; VI = variable interval.
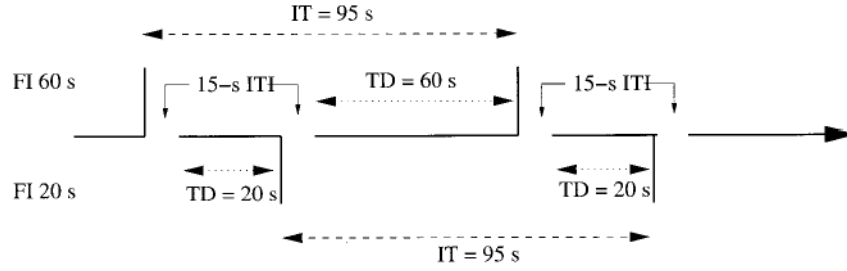
Figure 5.
Temporal relations in the concurrent schedule used in Experiment 2. Vertical lines above the solid horizontal arrow indicate reinforcers earned on the FI 60-s schedule; vertical lines below the arrow indicate reinforcers earned on the FI 20-s schedule. Blank spaces after a reinforcer indicate a 15-s intertrial interval (ITI). The reinforcer on the FI 20-s (respectively, the FI 60-s) key was scheduled 20 s (respectively, 60 s) after the beginning of a trial if the last reinforcer had been collected on the FI 60-s schedule (respectively, the FI 20-s schedule). As a consequence, the time between two successive reinforcers (the trial duration; TD) was 20 s on the FI 20-s schedule and 60 s on the FI 60-s schedule, whereas the time between two successive FI 20-s reinforcers or two successive FI 60-s reinforcers (the interreinforcement time; IT) was 95 s. FI = fixed interval.
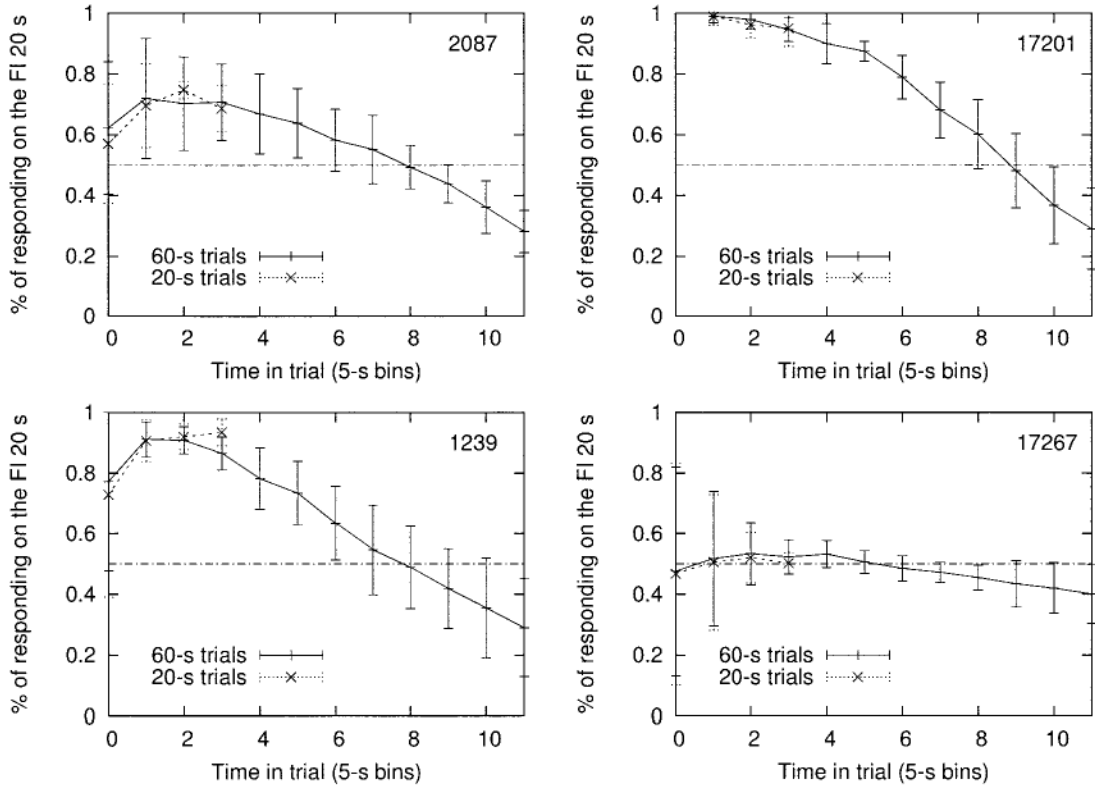
Figure 6.
Proportion of responding on the FI 20-s schedule in the concurrent procedures of Experiment 2. Proportions are plotted as a function of the time elapsed since the beginning of the trial. Twenty-second trials (terminating with a reinforcer on the FI 20-s schedule) and 60-s trials (terminating with a reinforcer on the FI 60-s schedule) are shown separately. Data are averages from the last three sessions before a reversal, averaged over reversals. Horizontal dashed lines indicate indifference points; error bars are standard deviations. FI = fixed interval.
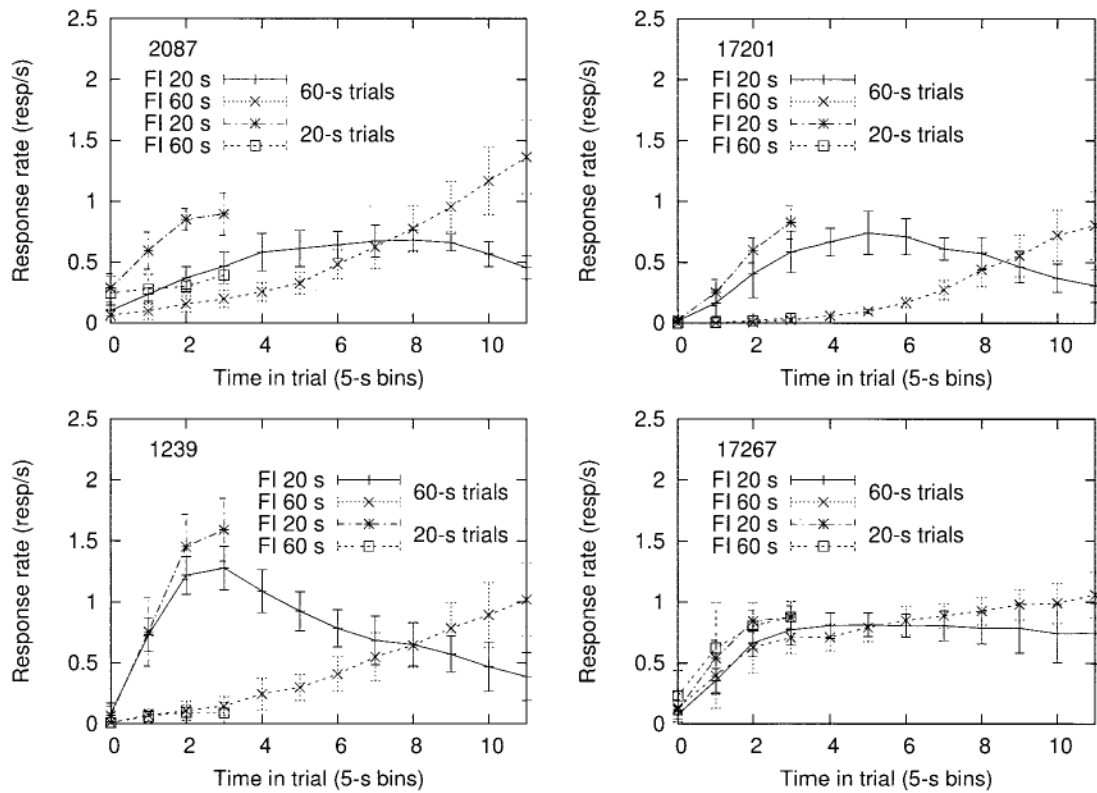
Figure 7.
Response rate on the FI 20-s and FI 60-s schedules for individual pigeons in the concurrent procedures of Experiment 2. Rates are plotted as a function of the time elapsed since the beginning of a trial. Twenty-second trials (terminating with a reinforcer on the FI 20-s schedule) and 60-s trials (terminating with a reinforcer on the FI 60-s schedule) are shown separately. Data are averages from the last three sessions before a reversal, averaged over reversals; error bars are standard deviations. resp/s = responses per second; FI = fixed interval.
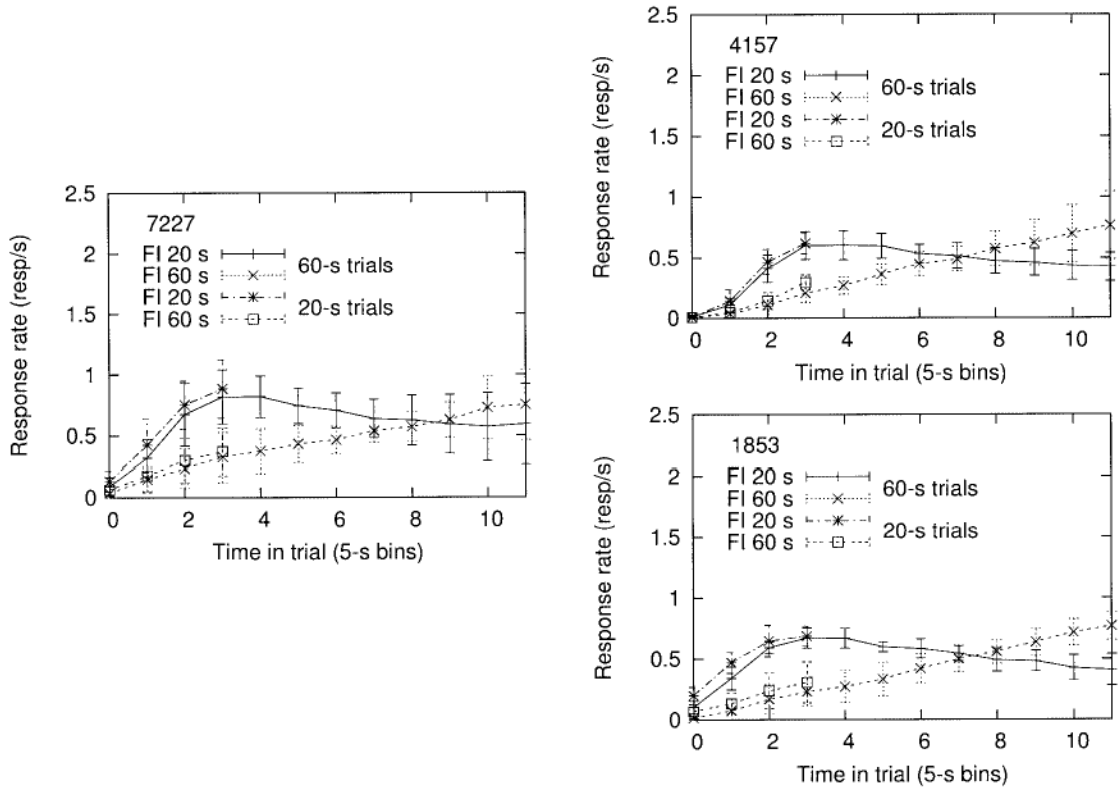
Figure 8.
Response rate on the FI 20-s and FI 60-s schedules for individual pigeons in the replication of Experiment 2, with the 15-s intertrial blackout omitted. Rates are plotted as a function of the time elapsed since the beginning of a trial. Twenty-second trials (terminating with a reinforcer on the FI 20-s schedule) and 60-s trials (terminating with a reinforcer on the FI 60-s schedules) are shown separately. Data are averages from the last three sessions before a reversal, averaged over reversals; error bars are standard deviations. resp/s = responses per second; FI = fixed interval.
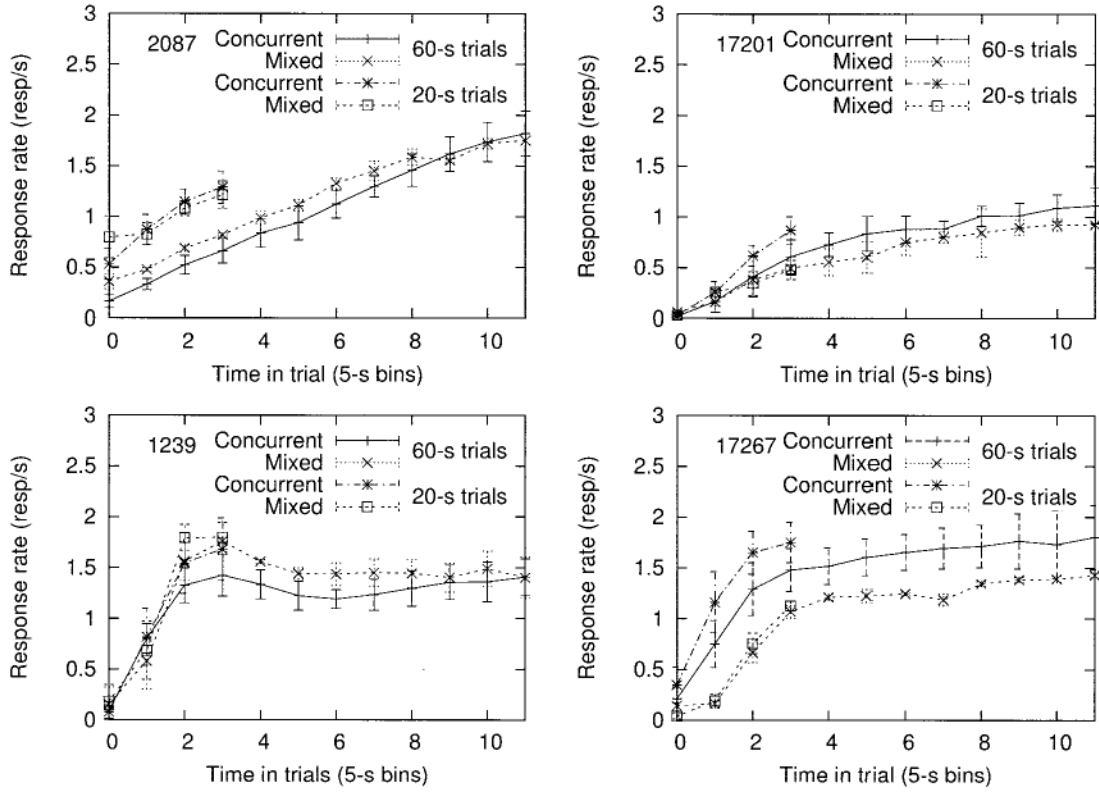
Figure 9.
Overall response rate as a function of time since the beginning of a trial for individual pigeons in the concurrent and mixed conditions of Experiment 2. Data are averages from the last three sessions before a reversal, averaged over reversals; error bars are standard deviations. resp/s = responses per second.
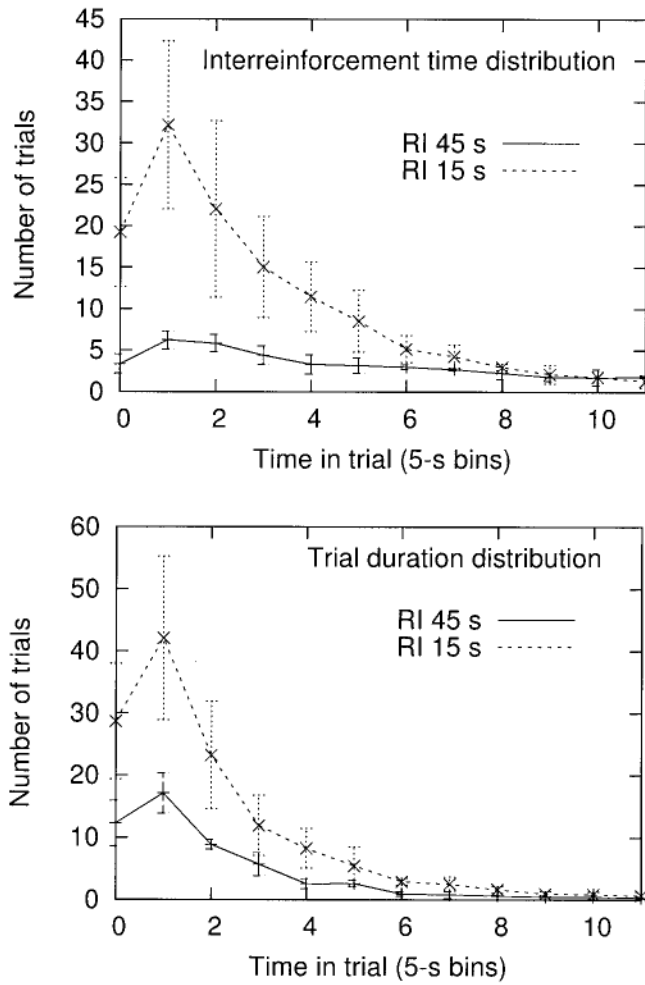
Figure 10.
Interreinforcement time (top) and trial duration (bottom) distributions in a concurrent RI 15-s–RI 45-s schedule. Data are averaged from Cerutti and Staddon (2004b, Experiment 3); error bars are standard deviations. RI = random interval.

Table 1

Mean Number of Trials Ending Within a Given Range of Time to Reinforcement on FI and VI Schedules for Each Pigeon in the Resetting Condition of Experiment 1

| Subject | FI | VI | | | | | |
	60–65	35–40	40–45	45–50	50–55	55–60	60–65
2189							
M	48.08	0.25	0.33	0.16	0.08	0.08	0.16
SD	1.55	0.43	0.47	0.37	0.27	0.27	0.37
2087							
M	49.00	0.00	0.00	0.00	0.00	0.16	0.25
SD	0.50	0.00	0.00	0.00	0.00	0.37	0.43
17267							
M	48.33	0.16	0.33	0.25	0.16	0.16	0.08
SD	1.06	0.37	0.47	0.43	0.37	0.37	0.27

Note. Ranges are in seconds. FI = fixed interval; VI = variable interval.