

BRIEF REPORT

Pigeons Learn Signal-Food Intervals Independently in a Multiple Peak Procedure

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Previous research has shown rapid learning of multiple temporal relations between signals and food by pigeons when these relations are changed unpredictably each session (Kyonka & Grace, 2007). The goal of the present study was to test whether contextual temporal cues—that is, an alternative signal-food delay that was a valid predictor of a target signal-food delay—facilitated acquisition by the target contingency. Four pigeons responded in a multiple peak-interval procedure in which red and green keys signaled separate fixed-interval (FI) schedules with occasional extinction probes (peak trials). The schedule parameters of the FIs either summed to 30 s (correlated condition; $\rho = -1.0$) or were not restricted to sum to 30 s (uncorrelated condition; $\rho = 0.0$). Comparing stop times obtained from peak trials in the 2 conditions revealed no effect of context: Temporal control of responding was acquired at the same rate and with the same precision regardless of whether the schedule values were correlated. These results suggest that pigeons learn about multiple signal-food delays independently.

Keywords: acquisition and dynamics of temporal control, multiple-cue temporal integration, peak-interval procedure, stop times, pigeons

Supplemental materials: <http://dx.doi.org/10.1037/xan0000011.supp>

The ability to adapt in the face of environmental changes is essential for an organism's survival, and such adaptation often depends on detecting relationships among multiple temporal contingencies. For example, if an organism forages for food in different patches, the time to food availability in one patch may be negatively correlated with time to food availability in an alternative patch. Thus, an important goal for research is to understand the extent to which adaptation to a target temporal contingency depends on information provided by additional temporal contingencies that are correlated with the target. In this study, we investigated temporal integration by exploring the contribution of multiple temporal cues to adaptation of stop times (a measure of temporal control). The peak procedure (Roberts, 1981) is a mod-

ified fixed-interval (FI) schedule of reinforcement with occasional peak-interval (PI) probes pseudorandomly interspersed. The reinforcer is omitted on PI probes, which last much longer than FI trials so that it is possible to obtain measures of temporal control before and after the time of scheduled reinforcer delivery. The present experiment involved two peak procedures in a multiple schedule. Both schedules were changed pseudorandomly each session. If a measure of temporal control was obtained from a red PI trial, then the interval for the red component was the "target component FI" and the interval for the green component was the "context component FI." Across sessions, the pair of schedule values in the two components were either correlated (i.e., a longer FI in one component meant a shorter FI in the other) or not. We sought to determine whether this procedure would yield any evidence of temporal integration; that is, whether animals would learn FIs faster when the two schedule values were correlated than when they were uncorrelated.

Temporal dynamics experiments involving schedules of reinforcement with frequently changing intervals have shown that responding can adjust rapidly to changes in interval duration. For example, Higa and colleagues have used response-initiated delay schedules with pigeons in which programmed interfood intervals were changed periodically (Higa, Thaw & Staddon, 1993) or cyclically (Higa, Wynne & Staddon, 1991). Mean pause time in the current trial was a linear function of the most recent interfood

This article was published Online First December 23, 2013 under the previous title (*Journal of Experimental Psychology: Animal Behavior Processes*).

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interval. Gallistel, Mark, King, and Latham (2001) showed that the adaptation of rats' responses to a concurrent variable interval schedule of electrical brain stimulation depended directly on the frequency of change. Research with Pavlovian procedures, such as autoshaping in pigeons, fear conditioning in rats and goldfish, and eyeblink conditioning with rabbits, also shows evidence for rapid learning of temporal intervals (see Balsam, Drew & Yang, 2002, for review).

Research with "rapid acquisition" choice procedures has studied how pigeons are able to learn temporal intervals that frequently change. In these procedures (e.g., Grace, Bragason & McLean, 2003; cf. Schofield & Davison, 1997), pigeons choose between two stimuli that are associated with different delays to food. The key feature is that one or both of the delays change unpredictably across sessions, so that behavior must adapt within a session if at all. Thus, rapid acquisition procedures that involve the peak procedure can be used to investigate temporal dynamics.

Kyonka and Grace (2007) used a concurrent-chains procedure to study the adaptation of choice and timing within sessions. In a typical concurrent-chains task (e.g., Grace, Sargisson & White, 2012), pigeons respond during a choice phase ("initial links") to produce one of two mutually exclusive outcome schedules ("terminal links"). In Kyonka and Grace's procedure, terminal links included PI trials to provide convergent measures of choice (response allocation during the initial links) and temporal control (start and stop times on PI trials; Grace & Nevin, 1999). They compared two conditions. In the "minimal-variation" condition, the terminal-link intervals were always 10 s and 20 s. The only potential change from one session to the next was whether the left or right initial link produced the shorter, 10-s terminal link. In the "maximal-variation" condition, the pair of terminal-link intervals was determined pseudorandomly such that the shorter terminal link was between 6 s and 15 s, and interval pairs in a session always summed to 30 s. Thus, in the maximal-variation condition, both short and long intervals and the side-key location of the shorter terminal link were changed from one session to the next.

Kyonka and Grace (2007) found that start and stop times from PI terminal links tracked the changes in programmed terminal-link intervals. Start and stop times were linear functions of the terminal-link intervals, and rapidly adapted to new values each session, stabilizing within the first half of the session. Interestingly, rate of acquisition did not significantly differ between the two conditions: Start and stop times stabilized as quickly in the maximal-variation condition as in the minimal-variation condition, even though there was, arguably, more to learn in the former. This result led Kyonka and Grace to speculate that subjects learned intervals anew in each minimal-variation session, even though they were always 10 and 20 s.

In Kyonka and Grace's (2007) study and subsequent research (Kyonka & Grace, 2008, 2009), terminal-link intervals typically have summed to a constant value (e.g., 30 s). Thus, across sessions, the intervals for the left and right schedules were perfectly negatively correlated: Relatively long intervals were always paired with relatively short intervals. Consequently, both the intervals for the target and alternative schedules could provide information about the temporal contingency for the target schedule. That is, current responding could be determined both by the current programmed interval and the programmed interval of the currently inactive schedule. The primary goal of the present study was to

determine whether the "contextual" temporal cue associated with the alternative schedule contributes to temporal control. If so, we predict that more precise temporal control and faster acquisition of responding should be evident when the schedule intervals are correlated compared to when they are uncorrelated. Previous investigation into temporal integration using spatial contexts has found that the interval that controlled behavior was influenced by the context in which acquisition occurred (Molet, Urcelay, Miguez, & Miller, 2010). Here, intervals are rapidly acquired within a session with a temporal context that is determined by the correlation of two separate interval schedules. If context influenced the acquisition and control an interval schedule has when spatial context was manipulated, it is possible that temporal context could likewise be manipulated and change the resulting rate of acquisition.

In our study, experimentally naïve pigeons were trained on a simplified version of Kyonka and Grace's (2007) procedure in which only the terminal-link schedules were presented, with the initial links replaced by an intertrial interval (technically, a multiple schedule). The schedules were signaled by red or green illumination of the center key. Schedule values and the key color associated with the shorter interval were determined pseudorandomly each session. In the correlated condition, the red and green intervals could range between 6 s and 24 s and always summed to 30 s ($\rho = -1.0$). In the uncorrelated condition ($\rho = 0.0$), red and green intervals were sampled independently from the same range for each session and on average summed to 30 s.

If contextual cues did not contribute to acquisition of temporal control and pigeons approached each session *de novo*, as suggested by Kyonka and Grace (2007), there should be no difference between the correlated and uncorrelated conditions in acquisition or precision of temporal control.

Method

Subjects

Four experimentally naïve pigeons (*Columba livia*) of mixed breed and sex, numbered 101–104, were maintained at 85% ad libitum weight plus or minus 15g through appropriate postsession feedings. Pigeons were housed individually in a vivarium with free access to water and grit and kept on a 12 hr light:dark cycle with windows providing natural light.

Apparatus

Four operant chambers (32 cm deep $\times$ 34 cm wide $\times$ 34 cm high) were enclosed in sound-attenuating boxes that contained ventilation fans. Each chamber contained three keys that were 21 cm above the floor arranged in a row 10 cm apart, a houselight located above the center key, and a grain magazine with a 5 cm $\times$ 5.5cm aperture that was centered 6 cm above the floor. The houselight provided general illumination at all times except during reinforcer delivery. The magazine, which was illuminated during reinforcement, contained wheat. A force of approximately 0.15 N was necessary to operate each key. Experimental events were controlled through a microcomputer and MED-PC® interface that was located in an adjacent room.

Procedure

Before training began, pigeons were trained to eat from the grain magazine, and an autoshaping procedure was used to train key pecking. After all subjects pecked for food, they were exposed to the multiple peak-interval procedure. With few exceptions, sessions were conducted at approximately the same time every day. Sessions ended after 72 trials or 70 min, whichever came first.

At the start of each trial, the center key was lit with either red or green; color was determined pseudorandomly. On FI trials, pecks to the center key were reinforced with 3-s access to wheat according to an FI schedule. On PI trials, the center key was lit for 60 s. There was no programmed consequence of a key peck at any point during a PI trial. After a trial ended, the key light was extinguished, and after a variable-time 8-s intertrial interval, the next trial began.

Stop times from individual PI trials were obtained using the method of Cheng and Westwood (1993). Responses in PI trials were sorted into 60 equal time bins of 1-s duration. The time of the last response before three consecutive empty bins was designated the stop time. Start times were obtained but are not reported because, consistent with previous research (Kyonka & Grace, 2010), stop times were more strongly related to programmed intervals than to start times.

The 72 trials in each session were arranged in six blocks of 12 trials. Each block included five FI trials and one PI trial assigned to each component (red and green). The programmed interval determined the time from stimulus onset to food availability in FI trials. Different intervals were programmed for red and green components in each session. The first red and first green PI trials occurred during block 1, the second pair occurred during block 2, and so forth. Intervals for a component stayed the same within a session but were changed across sessions.

There were two experimental conditions. We generated intervals for each session using the same approach Kyonka and Grace (2007) used to produce terminal-link delays in their maximal-variation condition. Three separate lists of intervals $30/(2^{X_n} + 1)$, with X_n s drawn from a uniform distribution with range [0, 2] were generated. For the correlated condition, if the n th term of a pseudorandom binary sequence (Hunter & Davison, 1985) was one, the n th interval from the first list was assigned to the red schedule. If that term was zero, the interval was assigned to green. The interval for the remaining key color was $30 - 30/(2^{X_n} + 1)$. In this way, the sum of red and green intervals always equaled 30 s, pairs of intervals were correlated ($\rho = -1$), and the log of the ratios of red to green intervals ranged uniformly from $\log(1/4)$ to $\log(4/1)$. Two lists were used to generate intervals in the uncorrelated conditions, one for red intervals and the other for green. Separate random binary sequences were generated for each list. If the n th term of the sequence was one, the n th interval in the list was used. If that term of the sequence was zero, 30—the n th interval was used. In this way, red and green intervals were independent ($\rho = 0$), but otherwise the same as those in the correlated condition. The range of possible intervals was 6 to 24 s; the sum of intervals from the two components equaled 30 s for each session; and the ratios of red:green intervals were uniformly distributed (in logarithmic terms) from 1:4 to 4:1. In the uncorrelated condition, two values were sampled independently from a uniform distribution [range: $\log(6)$ to $\log(24)$] for each session ($\rho = 0.0$). Logarithms were back-transformed to obtain intervals, in seconds, for the red and

green components. In this way, the average sum of the intervals across sessions in the uncorrelated condition was 30 s and delay ratios had the same potential range (1:4 to 4:1) as the correlated condition. In both conditions, the shorter interval was assigned to the red or green component according to the 31-step pseudorandom binary sequence similar to the one used by Hunter and Davison (1985).

All pigeons experienced 100 sessions of the uncorrelated condition, then 60 sessions of the correlated condition. To determine whether there were any trends in temporal control due to practice effects, pigeons were returned to the uncorrelated condition for 40 sessions. Data presented here are from the last 40 sessions of the uncorrelated and correlated conditions and from the 40 sessions in the uncorrelated replication. Sample sizes of 40 sessions had at least 84% power to detect predictors ($R^2 \geq 0.25$) for all single-subject analyses that produced parameter estimates used in within-subject group statistical analyses.

Results

To determine how temporal control developed with increased exposure to an interval over the course of a session, we calculated stop times for each PI trial. Stop times from individual trials were excluded if they were later than 57 s. At that point in PI trials, genuine stop times cannot be distinguished from continuous responding at a high rate. An average 4.01% (range: 2.64–5.69%) of stop times were excluded for each pigeon. Because continuous high-rate responding indicates a lack of temporal control, the number of excluded stop times was entered into a repeated-measures analysis of variance (ANOVA) with condition and block as factors. The ANOVA revealed a significant main effect of block on number of excluded stop times ($F(5, 15) = 49.52, p < .001, f^2 = 16.51, 95\% \text{ CI } [10.23, 38.70]$), but not of condition ($p = .45$) or the Condition $\times$ Block interaction ($p = .74$). Tukey's Honestly Significant Difference (HSD) tests showed that significantly more stop times were excluded from block 1 than from any other block. The mean programmed interval of PI trials with excluded stop times, 16.19 s ($SE = 0.54$), was not significantly different from the average programmed interval of 15 s, $t(3) = 2.20, p = .11$.

Figure 1 shows average stop times plotted as a function of the programmed interval that determined the availability of food on FI trials. Stop times adjusted to programmed intervals within sessions. In block 1, there was no systematic relation between stop times and the programmed interval, as shown by the nearly horizontal regression slopes across conditions ($M = 0.15, SE = 0.04$). Once pigeons had had more exposure to the programmed intervals, slopes of the best-fitting regression lines were positive, reaching $M = 0.98 (SE = 0.11)$ by block 6. Lines of best fit were also estimated for stop times from each pigeon and every block. With four exceptions (all from blocks 2 or 3 of uncorrelated conditions) slopes from blocks 2–6 were significantly greater than zero in all conditions, indicating that short intervals produced relatively earlier stop times, while longer intervals produced later stop times: Target component FIs controlled stop times in blocks 2–6.

Faster acquisition of temporal control or greater sensitivity to Lag 0 intervals for the target component (i.e., the interval currently in effect) in the correlated condition (indicated by larger regression coefficients) would suggest that the alternative component provided information that facilitated the acquisition of temporal con-

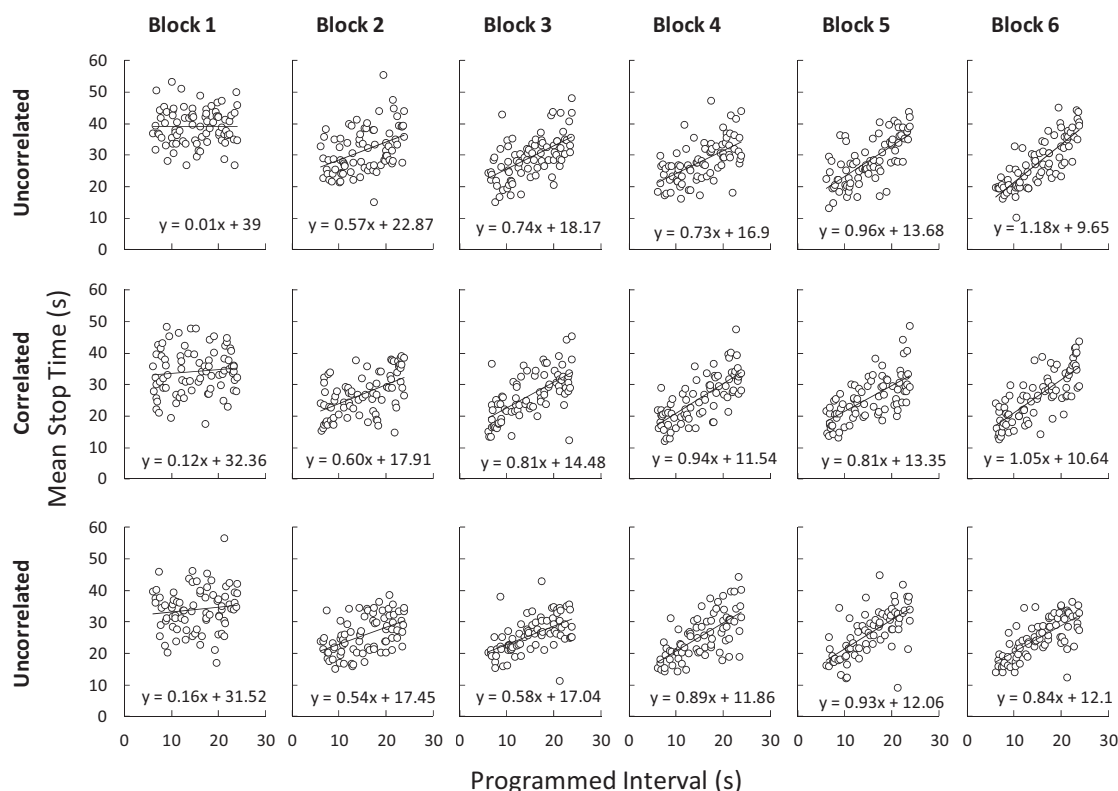


Figure 1. Temporal control developed within-session in all conditions. Stop times obtained from peak-interval (PI) trials for both red and green keys in blocks 1–6 (columns 1–6), as a function of the fixed interval (FI) value for the first uncorrelated condition (top row), correlated condition (middle row) and the uncorrelated replication (bottom row). Each circle is the mean stop time from a single PI trial, averaged across pigeons. Stop times of 57 s and longer have been removed from the figure (see text for further details). Solid lines are lines of best fit for averaged data. Equations for lines of best fit are shown at the bottom of each panel. Longer FI values produced later start times in blocks 2–6, as indicated by positive slopes of the regression lines. When exposure to the interval was less (block 1), there was no systematic effect of longer programmed intervals. Supplemental figures S1–S4 show stop times for individual pigeons.

trol in the target component. To determine when stop times adapted within sessions and to compare the pattern of adaptation across conditions, we regressed stop times onto the programmed intervals for each of the six blocks in a session, for each pigeon in each condition. Figure 2A shows mean regression slopes for each block and condition.

A repeated-measures ANOVA was conducted using the regression slopes from each pigeon as the dependent variable and block and condition as factors. The ANOVA revealed a significant main effect of block on slope $F(5, 15) = 36.92, p < .001, f^2 = 12.31, 95\% \text{ CI} [7.56, 28.81]$. Neither the effect of condition, $F(2, 6) = 0.07, p = .93$, nor the Condition $\times$ Block interaction, $F(10, 30) = 1.34, p = .25$, were statistically significant. Bayes factors assessing the relative strength of evidence for the null model versus each main effect were 1.03×10^{-8} for block and 7.22 for condition. Bayes factors greater than one support the null model: Sensitivity of stop times to programmed interval increased with exposure to the programmed interval, but did not differ by condition. Error bars in Figure 2A are 95% confidence limits on slopes for each block and condition. CIs for block 1 included zero but not one for all conditions. For blocks 1–4, the entire correlated condition CI overlaps with CIs for one or both of the uncorrelated conditions. The upper 66% of the correlated condi-

tion CI from block 5 and the lower 88% of the correlated condition CI from block 6 overlap with CIs for one or both of the uncorrelated conditions from the same block. Sensitivity increased over the course of a session, but was equivalent in the three conditions; there was no evidence of faster acquisition or greater sensitivity in the correlated condition.

Post hoc tests were conducted on the main effect of block to ascertain when stop times stabilized within a session. Tukey's HSD tests showed stop times stabilized by block 4: There were no statistically significant differences between stop times from blocks 4, 5, and 6. Together with the greater proportion of excluded stop times from block 1, post hoc tests indicated that stop times adjusted during the first three blocks but did not change significantly after the middle (i.e., the 36th trial) of a session. Therefore, for subsequent analyses we used the average of stop times obtained from the final three blocks of a session as estimates of asymptotic stop times.

For a quantitative assessment of the degree to which intervals from the current and previous sessions controlled responding, asymptotic stop times were regressed onto the programmed interval from the current session (Lag 0), as well as the programmed interval from FI trials in the previous two sessions (Lags 1–2). For example, stop times

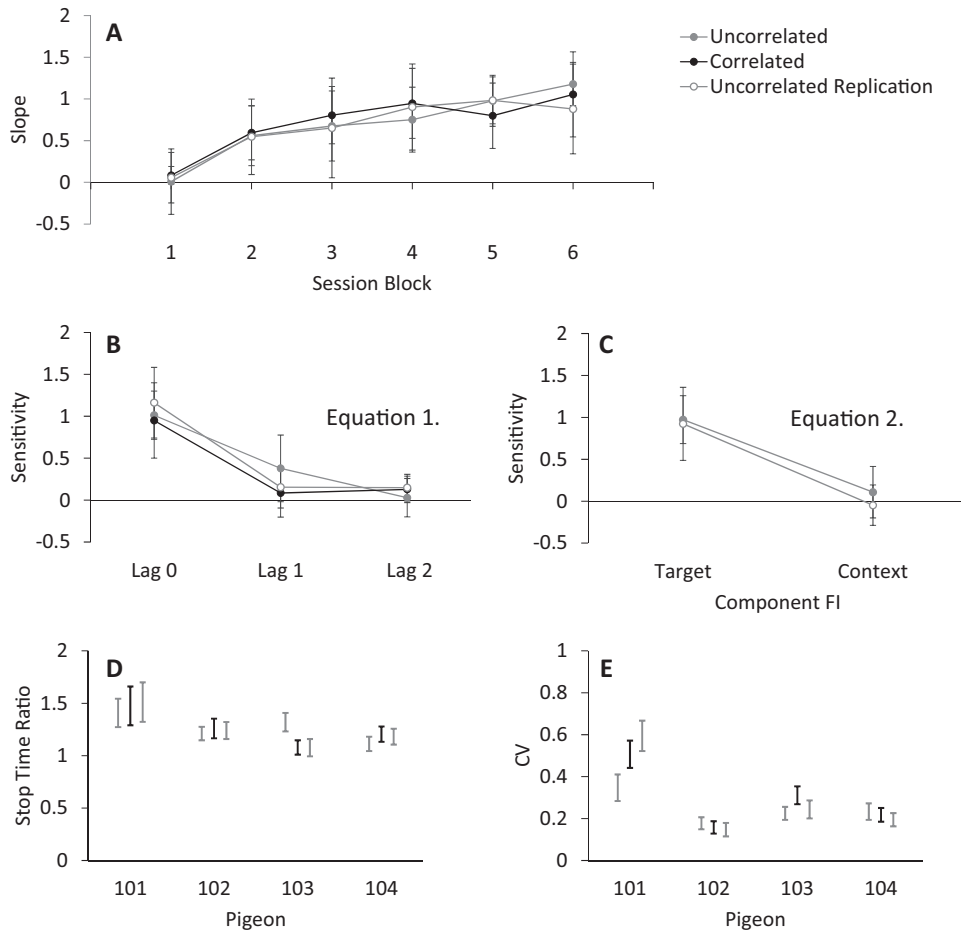


Figure 2. Sensitivity (unstandardized regression coefficients) of stop times to programmed fixed intervals (FIs) and summary measures of temporal control. In all panels, separate regressions were calculated for each condition and pigeon. Circles represent group means, bars show 95% confidence limits. **A:** Regression slope by block, obtained by regressing stop times from each block on programmed intervals. Temporal control developed within sessions and was not different for correlated and uncorrelated conditions. **B:** Group mean estimate of the three sensitivity parameters (a s) obtained from fitting Equation 1 to the arithmetic mean of stop times from blocks 4–6 of each session. Lag refers to the session that the interval was taken from relative to the session in which the stop times were obtained: the same session (Lag 0), the previous session (Lag 1), or two sessions prior (Lag 2). In all conditions, stop times were functions of the programmed interval from the current session but not of the programmed intervals from previous sessions. **C:** Mean estimates of the two sensitivity parameters (a s) obtained from fitting Equation 2 to the arithmetic mean of stop times from blocks 4–6 of each session with fixed intervals (FI). “Target component FI” denotes the predictor variable in the initial regression: the programmed interval in the component that corresponded with the stop time (e.g., if a stop time was obtained from a red peak interval [PI] trial, the schedule is the programmed interval in the red component). The “Context Component FI” refers to the programmed interval in the other component, the predictor that was added in the hierarchical regression. Target Component FI 95% CIs overlapped with each other and with one but not with zero; 95% CIs for Context Component FIs overlapped with each other and with zero, but not with one. In both uncorrelated conditions, stop times were functions of Target Component FIs but not Context Component FIs. **D:** Mean stop time from Blocks 1–3 of a single session with mean stop time from blocks 4–6 of the same session ratio comparisons, 95% CIs. **E:** Ninety-five % CIs for stop time coefficients of variation (CVs). With few exceptions, 95% CIs from all three conditions overlapped for each subject, indicating that relative variability was comparable in all three conditions.

from the red component were regressed on the corresponding Lag 0–2 intervals:

$$Stop_R = a_{R0}FI_{R0} + a_{R1}FI_{R1} + a_{R2}FI_{R2} + b \quad (1)$$

In Equation 1, FIs are programmed interval durations on FI trials. Letter subscripts (R and, hypothetically, G) indicate the

red or green component, respectively. Numeric subscripts indicate session lag. The three a parameters are unstandardized regression coefficients and b is a y -intercept. Larger regression coefficients in Equation 1 fits indicate greater control over current responding. If stop times were controlled by the current programmed interval only, the Lag 0 coefficient would be large

and positive and the Lag 1 and Lag 2 coefficients small and not significantly different from zero.

We fit Equation 1 to mean asymptotic stop times and obtained separate parameter estimates for each pigeon and condition. Figure 2B shows the mean unstandardized regression coefficients. For all pigeons in all conditions, coefficients were greatest for the Lag 0 interval. Mean Lag 0 coefficients in the uncorrelated, correlated and uncorrelated replication conditions, respectively, were $M = 1.01$ ($SD = .17$), $M = .95$ ($SD = .28$) and $M = 1.23$ ($SD = .28$). Only one higher-lag coefficient (Lag 2 in the uncorrelated replication for Pigeon 102, $\beta = 0.21$) was significantly different from zero. A repeated-measures ANOVA with regression coefficients as the dependent variable and condition and Lag as factors revealed a significant main effect of Lag, $F(2, 6) = 59.62$, $p < .001$, $f^2 = 19.46$, 95% CI [12.10, 45.66]. There was no effect of condition, $F(2, 6) = 2.92$, $p = .13$ or Condition $\times$ Lag interaction, $F(4, 12) = 1.36$, $p = .31$. Bayes factors assessing the relative strength of evidence for the null model versus each main effect were 4.65×10^{-5} for Lag—supporting the main effect of Lag—and 0.53 for condition, which is not conclusive support for either the full or the null model. The programmed interval in a session was the best predictor for responding in that session, with no evidence of control by intervals from prior sessions and no evidence of differences between conditions.

We conducted two analyses to test whether the contextual temporal cues provided by the alternative schedule influenced responding. First, we compared the rates of acquisition between conditions. Faster within-session acquisition of temporal control in the correlated condition would indicate that stop times were differentially sensitive to context intervals when the cues in the other component provided relevant information. The absence of an effect of condition on stop times' sensitivity to programmed intervals in both block-by-block linear regressions and Equation 1 fits confirmed that acquisition of temporal control was neither greater nor faster in the correlated condition. Error bars in Figure 2B are 95% CIs on coefficients for each Lag and condition. All Lag 0 CIs included one but not zero, all higher-Lag CIs included zero but not one. The upper 75%, 81% and 100% of the correlated condition CI from Lags 0–2, respectively, overlapped with CIs for one or both of the uncorrelated conditions from the same Lag. The absence of a main effect of condition or a Condition $\times$ Lag interaction indicate that sensitivity coefficients were similar in all conditions, and CIs show that, if anything, sensitivity was lower when intervals were correlated. Second, we regressed the stop times from the uncorrelated conditions on intervals for both target and alternative schedules. A significant coefficient for the alternative-schedule interval would demonstrate that responding in the target schedule was affected by the temporal context (i.e., alternative interval), although it was irrelevant, and the sign (negative or positive) would indicate contrast or assimilation, respectively. Note that this analysis could not be performed for the correlated condition because of multicollinearity.

Figure 2C shows results from a hierarchical regression of mean stop times from blocks 4–6 on the current-session FIs (Lag 0) from both components in the uncorrelated condition. Only Lag 0 intervals were used because Lag 1 and 2 intervals had no systematic effect on responding. If a stop time was obtained from a red PI

trial, then the interval for the red component was the “target component FI” and the interval for the green component was the “context component FI.” For stop times from green PI trials the intervals for the green key were the target component FIs and those for the red key were the context component FIs:

$$\begin{cases} Stop_R = a_{R0}FI_{R0} + a_{G0}FI_{G0} + b \\ Stop_G = a_{G0}FI_{G0} + a_{R0}FI_{R0} + b \end{cases} \quad (2)$$

Subscripts and parameters in Equation 2 are as in Equation 1. The FI from the target component was the only predictor variable in the initial regression; the FI from the context component was added in a subsequent step.

For all pigeons and in both uncorrelated conditions, the target FI coefficient was always larger than the context FI and statistically significantly greater than zero. Only one context FI coefficient was significantly different from zero (Pigeon 103, first uncorrelated condition, $\beta = 0.37$). Half of context FI coefficients were negative, and across pigeons and replications, the average increase in variance accounted for in the second step of the regression was .011 ($SE = .006$). Averaged across pigeons and replications, the target and context FI coefficients were 0.95 (range: 0.58–1.25) and 0.03 (range: –0.22–0.37), respectively. This indicates that asymptotic stop times in the uncorrelated condition were a linear function with slope ~ 1 of the target-schedule interval, and were unaffected by the interval for the alternative schedule.

Stop times were relatively long early in sessions when exposure to component FIs was limited and tended to decrease as exposure to component FIs increased. As an additional test of whether context had any effect on stop times in the target component, the ratios of the average stop times from blocks 1–3 to the average stop time from block 4–6 were calculated for each session for individual pigeons. If stop times decreased over the course of the session, the ratio would be greater than one. Any difference in ratios across conditions would indicate a difference in sensitivity of stop times to target interval. In each condition the ratios were similar: The average ratios were 1.26 ($SE = 0.06$), 1.25 ($SE = 0.08$) and 1.25 ($SE = 0.09$) in the uncorrelated, correlated and uncorrelated replication conditions, respectively ($F < 1$). The Bayes factor assessing the relative strength of evidence for the null model versus a main effect of condition was 7.84, indicating strong support for the null. Figure 2D shows 95% CIs of these stop time ratios for each pigeon. With one exception (Pigeon 103, uncorrelated replication, lower limit = 0.99), 95% CIs all exceeded 1.0, indicating that stop times decreased over the course of a session. For Pigeons 101 and 103, the entire correlated Condition CI overlapped with CIs for one or both of the uncorrelated conditions. For Pigeons 102 and 104, respectively, the lower 83% and 86% of the correlated Condition CI overlapped with CIs for one or both of the uncorrelated conditions from the same Lag. This provides further evidence that temporal control was equivalent across conditions and that context did not play a significant role in determining stop times.

Sensitivity of stop times to the programmed interval in the target component was not greater or acquired more rapidly in the correlated condition. To evaluate the precision of temporal control, we calculated coefficients of variation for stop times for each session across the last three blocks, when behavior had stabilized. The coefficient of variation is the standard deviation divided by the

mean, and this value is widely used in research on timing as an index of relative accuracy (Church, 2002). To reduce bias due to small sample sizes, we calculated sample standard deviations by dividing by $N - 1$ rather than by N . This resulted in a more conservative (i.e., larger) estimated standard deviation for each session. Averaged across subjects, coefficients of variation were 0.25 ($SE = 0.04$), 0.30 ($SE = 0.08$), and 0.30 ($SE = 0.10$), for the uncorrelated, correlated, and uncorrelated replication conditions, respectively ($F < 1$). The Bayes factor assessing the relative strength of evidence for the null model versus a main effect of condition was 3.47, which supports the null. Figure 2E shows 95% CIs of coefficients of variation for each pigeon in each condition. Despite large between-subjects variability in coefficients of variation—stop times were more precise for some pigeons than others—relative variability for each pigeon was generally consistent across conditions. The entire correlated-condition CI overlapped with CIs for one or both of the uncorrelated conditions for Pigeons 102 and 104. For Pigeons 101 and 103, respectively, the upper 38% and lower 22% of the correlated condition CI overlapped with CIs for one or both of the uncorrelated conditions from the same Lag. The similarity of coefficients of variation suggests that temporal control was equally precise in the correlated and uncorrelated conditions.

Discussion

Pigeons were exposed to a multiple schedule in which both components were rapid acquisition peak-interval procedures. Programmed intervals for red and green components were changed pseudorandomly at the beginning of each session. In the correlated condition, the sum of red and green components equaled 30 s ($\rho = -1$) and in the uncorrelated conditions they were independent ($\rho = 0$). Analyses of stop times revealed that temporal control developed in both conditions, where longer FIs produced later stop times in PI trials. Stop times stabilized midsession and the rate of acquisition of temporal control was equivalent in both conditions. When stop times were regressed on Lag 0–2 FIs from the target component, the Lag 0 sensitivity coefficients were similar across conditions: Control by the current FI schedule was the same in correlated and uncorrelated conditions. These results indicate that pigeons did not integrate temporal context—the intervals in the alternative component—in the development of temporal control of stop times. In this experiment, the interval associated with the target schedule determined the break-run-break pattern observed on individual PI trials.

Comparisons of stop times, sensitivity coefficients, and ratios of average stop times all confirmed that there were no systematic differences in temporal control between correlated and uncorrelated conditions. Acquisition was not faster and stop times were no more sensitive to programmed intervals in the correlated condition, despite differences in the predictive utility of context component FIs. Hierarchical regression established that context component FIs did not control stop times in the uncorrelated conditions. Although temporal control developed within a session, the information provided by the context component did not contribute to the development or adaptation of stop times in this procedure. These results support Kyonka and Grace's (2007) assertion that pigeons approached each session *de novo*. This approach would have the advantage of minimizing proactive interference from

prior sessions, and might represent an example of adaptive forgetting (Kraemer & Golding, 1997).

Stop times in this experiment were comparable to previously reported stop times from experiments that used peak-interval procedures that were embedded in concurrent-chains (Kyonka & Grace, 2007, 2009, 2010). Whereas Kyonka and Grace used concurrent-chains procedures and pigeons that had previous experience with schedules of reinforcement, this experiment involved naïve pigeons as subjects and a multiple peak-interval procedure. In spite of these procedural differences, rates of acquisition and stabilization of stop times were similar. In the present experiment, when stop times were regressed on programmed intervals from current and previous sessions, coefficients for the Lag 0 interval were approximately 1 and the rate and trajectory of acquisition was similar to those reported previously. These results show that stop times can adapt rapidly to new intervals. In a multiple schedule, adaptation apparently proceeds in each component independently, even when each component potentially provides predictive information about the other.

In the present experiment, stop times were comparable in the correlated and uncorrelated conditions; whether the sum of the pair of intervals presented in a session equaled 30 s did not systematically affect temporal control. If the context component FIs had facilitated acquisition, acquisition in the correlated condition should have been either more rapid or more sensitive than it was in the uncorrelated conditions. It was neither. In the minimal-variation condition of Kyonka and Grace's (2007) experiment, the terminal links were always FI 10 s and FI 20 s, only the location of the shorter interval changed. In the maximal-variation condition, terminal-link FI schedules could take any value from 6 to 24 s. It could be expected that behavior would adjust more or more rapidly in the minimal-variation condition than in the maximal-variation condition, because, arguably, there was less to learn in the minimal- than the maximal-variation condition. Sensitivity of log initial-link response ratios to terminal-link immediacy ratios was higher in the minimal variation condition, but the trajectory of the acquisition remained unchanged.

Stop times adjusted within sessions without carryover control from previous sessions. Persistence of control across sessions may be adaptive in an environment that is fairly static. However, in unpredictably changing environments, it might be more adaptive for an organism to change its behavior in accordance with the contingencies in effect rather than attempt to discriminate whether reinforcement history or environmental context provide relevant information about reinforcement. In experimental preparations in which it is not possible for the subject to predict schedule values, this approach could facilitate contingency learning. While contextual control was not observed in the current experiment, a higher-order type of learning was observed—pigeons responded conservatively at the beginning of sessions and increased in precision throughout a session. This approach was not random responding but was instead systematic across all conditions of the experiment, indicating some higher-order learning and adaptation to the rapidly changing environment.

In the correlated condition of the present experiment and in related research (e.g., Kyonka & Grace, 2007), context has predictive value but contingencies change frequently. In such cases, behavior under the discriminative control of both the primary and context intervals might adapt faster or be more sensitive to changes

than behavior under discriminative control of the primary schedule alone. However, if faster acquisition and greater sensitivity do not produce discriminable differences in rate of reinforcement, control by the primary interval only would be a boundedly rational (Gigerenzer & Selten, 2001; Simon, 1957) approach. In the current experiment the value of the context was not manipulated. Future research might investigate whether temporal control can come under discriminative control of the context component if a greater advantage, such as a higher reinforcement rate, can be obtained.

In a similar set of studies, Caetano, Guilhardi, and Church (2012) arranged three differentially signalled FI schedules. Different response rates in the presence of the different stimuli demonstrated that rats' responding only came under temporal control of the intervals when presentation of the three schedules were intermixed within a session. When schedules were presented in successive blocks, temporal control was reacquired each block, indicating that response rates were controlled by temporal properties of the intervals rather than the distinctive visual or auditory properties of stimuli even though stimuli reliably signaled the upcoming FI. In their study and ours, temporal control was acquired within-session and determined by the target interval. Future research might investigate whether presenting the context FI concurrently during training might change how temporal acquisition develops within sessions.

Applied to the present experiment, theories and models of timing need not account for context—the additional information does not affect stop times. Instead, it appears that only the current component is the primary controlling variable for current responding. This implies that the pigeons' acquisition of temporal control is relatively "simplistic," meaning that pigeons may not take advantage of additional sources of information. This might have some adaptive value when an environment is continually changing, though it is difficult to assess or determine how that value is determined. Theories of timing that explain steady-state behavior might be poorly suited to explaining responding in a dynamic environment, because subjects approach each session de novo and there is no carryover between sessions. Additionally, such theories need not include contextual temporal cues, at least in this experimental arrangement. In dynamic environments, such as the one used in the present experiment, it is possible that the task is too complicated for this information to be used.

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Received May 13, 2013

Revision received September 25, 2013

Accepted October 8, 2013 ■