Human temporal learning with mixed signals

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ABSTRACT

The influence of cue informativeness on human temporal discrimination was evaluated using a peak-interval (PI) procedure. A target moved across the computer monitor, reaching the center at 2 or 4 s. Key presses shot the center of the screen. Participants earned points when shots hit the target and lost points for misses. The target was masked during occasional, extended PI trials, allowing for measurement of temporal discrimination. During PI trials, the screen background color could exert stimulus control by providing information about target speed. Cue informativeness was represented as the correlation ($\phi$) between light or dark green backgrounds and the 2- or 4-s target and was manipulated across 4 conditions: a multiple schedule ($\phi = 1$), mixed signals ($\phi = 0.8, 0.4$), and a mixed schedule ($\phi = 0$). In Experiment 1, participants were randomly assigned to one of the 4 conditions. In Experiment 2, each participant experienced all 4 conditions. Participants learned to respond at both intervals in all conditions. Cue informativeness did not affect peak time or spread. For the most part, temporal distributions of responses for the two background colors suggested a cover-both-bases strategy in the presence of mixed signals. Participants incorporated probabilistic information from cues to allocate responding in time.

1. General introduction

Cue informativeness, the extent to which stimuli predict reinforcer availability, is a potentially critical factor in response timing. When two or more reinforcement schedules are in effect, multiple and mixed schedules represent opposite endpoints of cue informativeness. Two or more discriminative stimuli in a multiple schedule signal unique outcomes. For example, a red light always precedes a fixed-interval (FI) 2-s schedule and a green light always precedes an FI 4-s schedule. In contrast, all stimuli signal the same outcome in a mixed schedule. A typical mixed schedule consists of one stimulus preceding two or more reinforcement schedules. For example, a red light precedes an FI 2- and 4-s schedule. In theory, any number of stimuli can precede different outcomes in a mixed schedule. For example, a red and green light randomly and nondifferentially precede an FI 2- and 4-s schedule. With repeated exposure to multiple or mixed schedules, distributions of responding in time are differentiated across stimuli in multiple schedules and are undifferentiated across stimuli in mixed schedules (see Ferster and Skinner, 1957).

Under some circumstances, cues can be partially informative. If a stimulus light signals the availability of food in an operant chamber, but an electrical fluctuation causes the stimulus light to fail to initiate or darken when programmed to do so, the presence or absence of the light is a less than perfect indicator of food availability. Intermediate cue informativeness also occurs when teachers inadvertently provide incorrect prompts to students, athletes “fake out” their opponents, poker players bluff, and politicians fail to deliver on some of their campaign promises. The extent to which the rat, student, opponent, poker player, and voter attend and respond to these partially informative cues may depend on overall cue informativeness.

Several associative learning experiments have characterized the functional relation between mixed signals and response patterns. These experiments have involved manipulating cue-outcome correlations in nonhumans (see Miller and Matute, 1996 for a review; Wasserman, 1974) and in humans (e.g., Beesley et al., 2015; Van Hamme et al., 1993; Wasserman, 1996; Wasserman and Shaklee, 1984). For example, Wasserman (1990) presented participants with a hypothetical scenario in which the participant was an allergist who was trying to determine which food within a compound, Food AX or Food BX, caused an allergic promise. The participant was an allergist who was trying to determine which food within a compound, Food AX or Food BX, caused an allergic promise. The participant was an allergist who was trying to determine which food within a compound, Food AX or Food BX, caused an allergic promise. The participant was an allergist who was trying to determine which food within a compound, Food AX or Food BX, caused an allergic promise. The participant was an allergist who was trying to determine which food within a compound, Food AX or Food BX, caused an allergic promise.
allergic reaction following exposure to each compound. In Condition 0, a mixed schedule, allergic reactions occurred equally in the presence of both compounds. In Condition 1, a multiple schedule, allergic reactions only occurred to AX and not BX. In the other conditions, the allergic reaction was correlated highly (condition 0.75) moderately (condition 0.5) or slightly (condition 0.25) with AX. Along this 0–100% scale of predictiveness, causality ratings of A and B were linearly related to condition. Participants rated A and B equally likely to be the allergen in Condition 0. They rated A most likely and B least likely to be the allergen in Condition 1. Importantly, Wasserman demonstrated that humans' ratings were sensitive to cue-outcome correlations intermediate to the multiple and mixed schedule endpoints of cue informativeness.

Human response patterns were sensitive to cue-outcome correlations in discrete-trial associative learning experiments (Beesley et al., 2015; Wasserman, 1990). In those paradigms, cues helped participants distinguish what to do. Cues can exert additional stimulus control when a person expects a reinforcer for a response, but at different delays. For example, a forecast of afternoon thunderstorms provides information about whether to carry an umbrella, but also when one would be likely to use the umbrella. Signaling what to do and signaling when to do it are both important, but not necessarily equivalent behaviorally or neurologically (see Delamater et al., 2018). Behaviorally, attention can influence the accuracy of temporal discrimination (i.e., responding at the highest rate at the right time) without disrupting reinforcement rate. Thus, it would be beneficial to examine whether the pattern of responding in time is a function of the probability of different temporal intervals given mixed signals.

Temporal discrimination procedures, most of which are variants of FI schedules of reinforcement in which the first response following an interval of a specified duration is reinforced, can be used to model the functional relation between cue informativeness and response timing. In his multiple cued peak-interval (PI) procedure, Roberts (1981) measured rat lever presses for food in FI 20 s and FI 40 s trials. The two FI schedules were differentially cued by light or sound. Occasional “peak-interval” (PI) trials began with the onset of one of the FI cues (light or sound). PI trials were extended in duration (around 80 s), and lever presses did not lead to food. Lever presses aggregated across several PI trials took the form of Gaussian curves that reached a maximum, or “peak time,” around the time of the FI-schedule duration (20 s or 40 s) with standard deviation, or “peak spread” proportional to the programmed interval.

Swanton et al. (2009) used a multiple cued peak interval (PI) procedure to evaluate whether cue informativeness influenced temporal discrimination. Rats nose poked for food on FI 10-s and FI 20-s schedules of food. These short and long intervals were signaled by a short or long cue (a light or a tone, counterbalanced across subjects). During training, they introduced occasional, extended PI trials in which the light or the tone was presented with no food for nose poking. Response distributions in PI trials were Gaussian with scalar variance. The highest rate of nose poking (peak time) was around the time of the FI schedule value associated with the cue. The standard deviation (peak spread) of the response distribution to the short cue was around half of that of the long cue. Swanton and colleagues evaluated the influence of cue informativeness in a testing phase during which the PI trials consisted of presenting the light and tone together as a compound stimulus. They suggested that response distributions in these testing PI trials could take any of several forms. First, the subject could “cover both bases” by responding at a high rate at both 10 and 20 s. Second, the subject could use an “either/or” strategy in which they respond at either the short or the long interval. Third, the subject could use an “averaging” strategy in which they combine their temporal learning into a single interval value somewhere between the short and the long interval. Swanton and colleagues found that response distributions in testing PI trials best conformed to the averaging account. That is, both the peak time and the peak spread was an average of the obtained peak time and peak spread in the training PI trials.

Although Swanton et al. (2009) found that rats averaged temporal information when presented with two stimuli associated with two different FI schedules, research using mixed FI-FI schedules in which a single stimulus is associated with a short and long interval suggests that animals cover both bases in those schedules (Catania and Reynolds, 1968; Leak and Gibbon, 1995; Sanabria and Oldenburg, 2014; Whitaker et al., 2003, 2008). That is, animals respond at a high rate at the short interval and the long interval according to the momentary conditional probability of the reinforcer.

Stimulus control of peak time and peak spread by cues other than time (e.g., light or sound) can be evaluated by manipulating signals present during FI trials of the PI procedure. Subramaniam and Kyonka (2019) examined pigeons’ responding in a PI procedure with mixed and multiple FI-FI schedules. The procedure consisted of two key light colors- the short and long color, FI 2- and 4-s schedules of food, and occasional, 12-s PI trials. A phi (φ) correlation is a measure of the association of two binary variables. The phi (φ) correlation between programmed interval duration (FI 2 and FI 4-s schedules) and key color (i.e., short, and long color) determined cue informativeness in each condition. The φ = 1 condition was a multiple schedule in which the short color signaled FI 2-s trials and the long color signaled FI 4-s trials. The φ = 0 condition was a non-traditional mixed schedule in which the short and long colors signaled both FI 2-s and 4-s trials with equal probability. At intermediate correlations (φ = 0.8, 0.6, 0.4, and 0.2), the short color was presented on most FI 2-s trials, but the long color was presented on occasional FI 2-s trials and the short color was presented on some FI 4-s trials. The primary dependent variables were obtained from distributions of key pecking in PI trials. PI response distributions differed as a function of key color when the cue-interval correlation was φ = 0.8 or higher but were not statistically distinguishable when the cue-interval correlation was φ = 0.6 or lower. A summed Gaussian function with two modes (Sanabria and Oldenburg, 2014; Whitaker et al., 2003, 2008) was used to estimate two peak times and two peak spreads.

If pigeons in Subramaniam and Kyonka’s (2019) experiment averaged temporal memories, there would have been a single peak time in between 2.0 s and 4.0 s – perhaps at the weighted geometric mean of the intervals. If they did not average temporal memories, Subramaniam and Kyonka predicted that there would be a peak time near the likely interval (~2 s for the short color and ~4 s for the long color) and a second peak time near the unlikely interval (~4 s for the short color and ~2 s for the long color). Peak times at likely intervals were accurate for all cue-interval correlations. Peak times at unlikely intervals were accurate when cue-interval correlations were low, but less accurate when cue-interval correlations were high. Pigeons did not average temporal memories, but the drift in peak times for the unlikely intervals suggested that the accuracy of temporal memories was limited by amount of exposure to the interval.

A similar PI procedure could be used to reveal the functional relation, if any, between temporal discrimination and attention to cues in human participants. Guilhardi et al. (2010) developed a multiple-cued PI procedure to measure temporal discrimination that promoted relatively fast acquisition of multiple discriminations without the need for a distraction task to control for verbal chronometric counting. Participants played a target game on a computer in which their goal was to hit a bull’s eye target that moved from left to right across the screen. In regular trials, the participant could press a key on the computer keyboard to shoot at the center of the screen while they could see the target. The FI 1 or target duration was 1 second and the target reached the center of the screen and was manipulated by changing the velocity of the target. Three target durations were differentially signaled by three different screen background colors. Shots hitting the target earned points and misses (i.e., shots occurring too early or late) lost points. Occasional PI trials did not differ from regular trials in screen background color, responses, or point contingencies, but a white rectangle masked the target from view. These PI trials allowed for a measurement of pure temporal discrimination because momentary feedback...
about whether shots hit the target was not available. When the three durations were intermixed during training, response distributions averaged across PI trials took the form of Gaussian curves that reached a maximum around the time participants earned points in regular trials.

The current study was a systematic replication of Subramaniam and Kyonka (2019) using Guilhardi et al.’s (2010) target game to model the relation between cue informativeness on attention and temporal discrimination in humans. As in Subramaniam and Kyonka (2019), the time to point availability was always 2 s and 4 s. Two background colors served as cues. Cue-interval correlations were manipulated across four conditions: A multiple schedule in which \( \varphi = 1 \), a mixed schedule in which \( \varphi = 0 \), and two intermediate-correlation conditions (\( \varphi = 0.8 \) or 0.4). We examined the functional relation between cue informativeness and temporal discrimination using a between-subjects design (Experiment 1) and a repeated-measures design (Experiment 2).

2. Experiment 1 introduction

In Experiment 1, participants were randomly assigned to a single cue-interval correlation. The objective was to establish whether cue informativeness would affect response timing in the same way that it affected choice in previous experiments (Beesley et al., 2015; Wasserman, 1990). If response patterns were sensitive to cue informativeness, then we expected that the two cues (background colors) would produce different response patterns when the cue-interval correlation was high and similar response patterns when the cue-interval correlation was low.

3. Method

3.1. Participants

Forty-eight participants, 38 who self-identified as females and 10 who self-identified as males, were recruited from psychology courses at a large Mid-Atlantic university. Participants were required to be at least 18 years old, have normal or corrected-to-normal binocular vision, and have avoided taking prescription or non-prescription drugs that affected their mood or energy levels. Participants earned research credit and a chance to win a gift card valued at $50. All participants completed one condition of the experiment within one visit to the laboratory lasting less than 1 hr.

3.2. Setting

Participants completed study procedures in groups in a 10-station classroom or a 2-station computer laboratory. Each participant sat at a desk or station containing one desktop computer with a monitor, keyboard, headphones, and mouse. Auditory stimuli were presented using a pair of stereo headphones. The color monitor presented visual stimuli using manufacturer recommended display settings (native resolution, standard brightness, standard contrast). Responses on the keyboard were recorded by the computer program. Participants responded by pressing the enter key and the spacebar key on the computer keyboard. The custom Microsoft Windows program, written in Microsoft Visual Basic © programming language, timed events with a 1-ms resolution, presented contingencies, and collected real-time experimental data.

3.3. Procedure

All study procedures were reviewed and approved by the University Institutional Review Board (IRB) and were carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki). When participants arrived at the laboratory, a researcher provided them with an informed consent form and obtained written consent from participants individually or in groups. Following consent, participants received instructions and completed the PI procedure, which was a variant of the Guilhardi et al. (2010) target game. Before the session, each computer monitor displayed the following instructions:

“During training, a target will move across your screen. You can press the ‘enter’ key every time you would like to shoot at the middle of the screen. Your goal is to hit the target as much as you can so you maximize your points. Points: −1 for missing the target, +1 for hits anywhere in the target, +5 for the bull’s eye. During testing, you won’t be able to see the bull’s eye but you will be able to shoot at the middle of the screen and score points. You can gain points by shooting the target more than once. You automatically lose 10 points if you do not respond during testing. You can take a break at any time by delaying the start of the trial. Good luck! Click the target on the right to continue.”

The researcher read the instructions to the participant and was available to answer questions, but did not inform participants of the time to point availability. After the participant clicked the target, the instruction, “Press the spacebar to begin,” appeared on the top center of the computer screen. Following a spacebar press, the first trial of the session began.

A session consisted of 60 regular trials and 60 PI trials. The first 20 trials were exposure trials in which participants responded in 10 short-target and 10 long-target regular trials (described below). The target moved across the screen from left to right and the background color was either light or dark green as shown in the top panel of Fig. 1. This initial exposure to regular trials was programmed to increase the likelihood that participants learned each target duration and could observe the relation between the target duration and background color. The exposure trials were followed by five blocks of 20 trials each. Participants completed eight regular trials and 12 PI trials in each block. These trials were presented in random order within blocks.

Across all trials, the time it took to hit the target to reach the center of the screen was either 2 s (short target) or 4 s (long target). These durations were used in previous research with pigeons (Subramaniam and Kyonka, 2019) and humans (Guilhardi et al., 2010), and were discriminable by both species.

Participants fired shots at the center of the screen by pressing the enter key. Each enter key press resulted in one shot. Each shot resulted in immediate visual feedback consisting of a yellow square 10 pixels across visible for 0.1 s on the center of the screen and auditory feedback (a clicking noise). Participants earned 5 points for each shot hitting the central blue circle (bull’s eye), one point for each shot missing other parts of the target, and lost 1 point for each shot missing the target. Participants lost 10 points for failing to respond in a trial. Illustrations of shots hitting and missing the target are shown in Fig. 1.

During regular trials, the target was visible, and moved across the screen from left to right. Because each target exited the screen after it reached the center, the total duration of each regular trial was two times the time to point availability. That is, short-target regular trials were 4 s long (2 s for the target to reach the center and 2 s to leave the screen) and long-target regular trials were 8 s long (4 s to reach the center and 4 s to leave the screen). The target was the same shape and relative size across the entire experiment: Five concentric circles that were red or white on the outside, and blue in the center, with a diameter 10% of the width of the computer monitor (102 pixels). Fig. 1 contains screenshots of the bull’s eye at the center of the screen in regular trials with the short and long background. With each shot taken during regular trials, participants could observe whether they hit the target by viewing the visual feedback (the yellow square) relative to the target.

During PI trials, a white rectangle covered the bull’s eye target trajectory, but the light or dark green background color was visible (see Fig. 1 for screenshots). Each enter-key press resulted in the same visual and auditory stimuli as regular trials, but the position of the yellow square relative to the target was not observable. Instead, the yellow square flashed on the center of the screen above the white rectangle. We
used several strategies to promote responding in PI trials. As in a previous study (Guilhardi et al., 2010), the identical point contingency as regular trials (i.e., 5 points for a bull’s eye, 1 point for a hit, and −1 point for a miss) was in effect during PI trials. Following pilot testing, we found that some participants would still not respond when the target was masked. To promote at least one response per PI trial, participants automatically lost 10 points if they did not respond. Pilot testing also revealed that when all PI trials were 12 s, response latencies were disrupted on the next trial. Therefore, we promoted attending to the task using a variable PI duration averaging 12 s throughout the session (range = 8–24 s).

Each regular and PI trial was followed by an intertrial interval (ITI). Participants controlled ITI duration. During the ITI, the computer monitor displayed feedback about points. Points earned in the previous trial were displayed on the top and center of the screen and cumulative points earned across the session were displayed on the top, right-hand side of the screen. The instruction, “Press the spacebar to begin,” was displayed on the center of the screen below the point feedback. A press to the spacebar began the next trial.

Participants were randomly assigned to complete one session of one of four cue-informativeness conditions (N = 12 per condition). The difference between conditions was the correlation between light or dark background color and the short or long target. This relation was expressed as phi ($\phi$) coefficients of $\phi = 1$ (multiple schedule), 0.8, 0.4, or 0 (mixed schedule). In the $\phi = 1$ condition, one background color (the “short background”) always signaled the short target and the other background color (the “long background”) always signaled the long target. In the $\phi = 0$ condition, the background colors were not correlated with the short and long targets. All short- and long-target regular trials occurred in the presence of the short or long background with equal probability. Thus, in the $\phi = 0$ condition, the background was uninformative of whether a short or long target was in effect.

In the moderately informative conditions ($\phi = 0.8, 0.4$), occasional short and long target trials were preceded by the long and short background color, respectively. We call these trials “miscued” trials and we manipulated cue informativeness by programming different numbers of “miscues” per session. In the $\phi = 0.8$ condition, three short- and long-target regular trials were miscued per session. To ensure that miscued trials were distributed throughout the session, one short- and one long-target miscue occurred during the first 20 trials of the condition; the other four miscues were presented during the 40 remaining regular trials with the constraint that a maximum of one miscue occurred in each block of 8 regular trials. In the $\phi = 0.4$ condition, nine short- and long-target trials were miscued per session. Three short- and three long-target miscues occurred during the first 20 regular trials of the condition; the other 12 miscues were presented during the 40 remaining regular trials with the constraint that no more than three miscues occurred in each block.

### 3.4. Results

Fig. 2 shows normalized rate of enter key presses as a function of time in the presence of the short and long background color PI trials averaged across all PI trials in a session and across groups of 12 participants in each cue-informativeness condition. By visual inspection, response distributions were more similar when cue-interval correlations were low than when they were high. Estimates of temporal discrimination (i.e., peak times and peak spreads) were calculated for individual participants using curve fitting procedures described below. In addition, we quantified the magnitude of stimulus control using an analysis of the nonoverlapping portion of response distributions in the presence of short and long background colors.

### 3.5. Curve fitting and model comparison

For a quantitative assessment of temporal discrimination, we fit single and summed Gaussian curves to each PI response distribution. Eq. (1), the single Gaussian, was as follows:

$$G(M, SD) = a \cdot e^{-\frac{(t - M)^2}{2SD^2}}. \tag{1}$$

where $a$ is the maximum response rate (peak height), $M$ is the peak time,
and SD is the peak spread. Eq. (1) describes PI performance when cues are highly informative of specific FI schedules, as they are in a multiple cued PI procedure.

Previous research has found that nonhumans respond according to the momentary conditional probability of reinforcement in this PI procedure (Subramaniam and Kyonka, 2019) and in mixed FI-FI schedules (e.g., Catania and Reynolds, 1968; Leak and Gibbon, 1995; Sanabria and Oldenburg, 2014; Whitaker et al., 2003, 2008). In other words, they respond as if the reinforcer will be available at both the short and long intervals. In these contexts, PI performance has been described using Eq. (2), which is the sum of two Gaussian curves:

\[ f(t) = K_1 \times G(M_1, SD_1) + K_2 \times G(M_2, SD_2), \]  

where \( K_1 \) and \( K_2 \) are scaling constants for the first and second Gaussian, respectively. \( M_1 \) and \( M_2 \) are peak times, and \( SD_1 \) and \( SD_2 \) are peak spreads.

Eqs. (1 and 2) were fit to normalized response distributions from each participant at each cue-interval correlation. The single Gaussian was defined in terms of three parameters (i.e., \( a, M, \) and \( SD \)); the summed Gaussian had seven free parameters (i.e., \( a_1, a_2, M_1, M_2, SD_1, SD_2, \) and \( K_1 \)). Nested model comparison involved calculating an F ratio that determined whether the superior fit of the full model was sufficient to justify the additional free parameters, compared to the reduced model (note that the reduced model had two free parameters because \( a = 1 \) in the normalized distributions). Estimates of parameters were obtained for all conditions and participants using a nonlinear optimization procedure (Microsoft Excel Solver).

Fig. 2 shows single (Eq. 1) or summed Gaussian (Eq. 2) curves fit to PI distributions (mean VAC = 0.91, range 0.17–0.999). If one Gaussian was a better fit to response distributions, then a curve with one mean and standard deviation was graphed, if the summed Gaussian was a better fit, then a curve with two means and standard deviations was graphed. Across individual participants, the summed Gaussian function was a better fit than the single Gaussian for a small proportion of distributions (35 out of 96, or 36.46%). A majority of distributions had single peaks, which indicates that, for most participants, the short and long background colors were each associated with a single interval.

Table 1 shows average peak time and spread for each cue-informativeness group and across all participants. If Eq. (1) was a better fit, the first and second peak time (\( M_1 \) and \( M_2 \)) and spread (\( SD_1 \) and \( SD_2 \)) were obtained from fits to response distributions across short-background PI trials (subscript 1) and long-background PI trials (subscript 2), respectively (light and dark green trials for \( \varphi = 0 \)). If Eq. (2) was a better fit, the first and second peak time and spread were an average of \( M_1, SD_1, M_2, \) and \( SD_2 \) from all PI trials.

Across all participants, background colors, and cue-informativeness conditions, first and second peak times (i.e., \( M_1 \) and \( M_2 \) in Eq. (2) or \( M \) from the single Gaussian) were 2.98 s (SE = 0.12 s) and 3.99 s (SE = 0.08 s), respectively. A mixed ANOVA with first or second peak time as the within-subjects factor and condition (\( \varphi = 1, 0.8, 0.4, \) or 0) as the between-subjects factor indicated that first peak times were statistically significantly earlier than second peak times, \( F(1,44) = 89.19, p < .001, \eta^2 = 0.67 \), but that there was no significant time by group interaction, \( F(3,44) = 1.43, p = .25, \eta^2 = 0.09 \) or main effect of group, \( F(3,44) = 1.62, p = .20, \eta^2 = 0.10 \). Cue informativeness did not affect the accuracy of temporal discrimination (when response rates peaked relative to each target interval).

First and second peak spreads (i.e., \( SD_1 \) and \( SD_2 \) or \( SD \)) were 0.66 s (SE = 0.07 s) and 0.94 s (SE = 0.11 s), respectively. A mixed ANOVA with first or second peak spread as the within-subjects factor and condition (\( \varphi = 1, 0.8, 0.4, \) or 0) as the between-subjects factor indicated that first peak spreads were significantly smaller than second peak spreads, \( F(1,44) = 6.98, p < .05, \eta^2 = 0.14 \), but that there was no significant spread by group interaction, \( F(3,44) = 0.97, p = .42, \eta^2 = 0.06 \) or main effect of group, \( F(3,44) = 1.43, p = .25, \eta^2 = 0.09 \). Cue informativeness did not affect the precision of temporal discrimination.

### 3.6. Quantifying differences in stimulus control by background color

Even though there were no systematic effects of cue informativeness on peak times or peak spread, cue informativeness may have affected how similar or different participants’ response patterns were in the presence of the two background colors. The nonoverlapping portion (NOP; Fox and Kyonka, 2015; Subramaniam and Kyonka, 2019) of short...
and long-background PI distributions quantifies the magnitude of differences in response rate over time depending on the background color.

To calculate NOP, we first calculated the sum of the absolute value of the difference between response rate (key presses per min) in short-background PI trials and response rate in long-background PI trials for each 0.5-s bin. To express NOP as a proportion ranging from 0 to 1, the maximum rate from each bin was summed, and NOP was divided by that total (i.e., the total possible NOP). An NOP of zero indicated complete overlap of short- and long-background PI distributions – no differentiation of response distributions by background color. If all responses on short-background PI trials occurred earlier in the trial than all responses on long-background PI trials, or vice versa, the distributions would not overlap, there would be complete differentiation of response distributions by background color, and NOP would be equal to one. We calculated NOP for each participant.

Bars in Fig. 3 show mean NOP proportion for each condition. If the degree of stimulus control that background color had over response distributions was related to cue informativeness, then NOP would be highest for $\phi = 1$ and lowest for $\phi = 0$. A one-way ANOVA confirmed that NOP differed across conditions, $F(3) = 6.77, p < .001, \eta^2 = 0.32$. Tukey HSD post-hoc tests revealed that NOP was statistically significantly higher when $\phi = 1$ (Mean = 0.77, SE = 0.06 responses) than when $\phi = 0.4$ (Mean = 0.44, SE = 0.6 responses) and $\phi = 0$ (Mean = 0.44, SE = 0.07 responses), both $p < 0.002$. NOP did not differ across $\phi = 1$ and $\phi = 0.8$ (Mean = 0.59, SE = 0.04 responses) conditions, $p = .17$. NOP was ordinally lowest when $\phi = 0.4$ and $\phi = 0$, and did not differ between these conditions with relatively low cue informativeness ($\phi = 0.30$).

4. Discussion

Experiment 1 was conducted to characterize the relation between cue informativeness and temporal discrimination in human participants using a between-subjects design. We asked how participants responded in a PI procedure given two intervals that were differentially, occasionally, or not signaled by two different screen background colors. Participants shot at a target by pressing enter in multiple or mixed PI 2- and 4-s schedules of points with occasional PI trials. For groups of 12 participants each, cue-interval correlations were either $\phi = 1$, $\phi = 0.8$, $\phi = 0.4$, or $\phi = 0$. Consistent with research on human temporal discrimination in multiple schedules (Guilhardi et al., 2010), when the cue-interval correlation was $\phi = 1$, temporal distributions of key presses were different for PI trials with different background colors. Distributions were more similar at intermediate correlations and when $\phi = 0$.

Most PI distributions were characterized by single rather than summed Gaussian functions. Summed Gaussian functions with two peak times would have indicated that responding was sensitive to the momentary conditional probability of points (e.g., Catania and Reynolds, 1968; Leak and Gibbon, 1995; Sanabria and Oldenburg, 2014; Subramaniam and Kyonka, 2019; Whittaker et al., 2003, 2008). Instead, single peaks could be evidence that response times were produced by averaging temporal memories of previous intervals (Swanton et al., 2009). In Experiment 1, average peak time for participants in the mixed schedule fell between the two peak times in the multiple schedule. If participants averaged temporal memories and responded accordingly, peak times (and perhaps peak spreads) in the mixed-schedule condition ($\phi = 0$) should be close to the average peak times from the multiple-schedule condition ($\phi = 1$) for the same participant. Assessing that possibility would require a within-subject experimental design.

5. Experiment 2 introduction

In Experiment 2, we used a within-subjects design to assess effects of cue informativeness on temporal discrimination when each participant responded to all levels of cue informativeness. Participants received the four cue-interval correlation conditions in either a descending (high-to-low $\phi$) or ascending (low-to-high $\phi$) order. One benefit to this within-subjects approach was that participants had extended contact with the temporal intervals in the PI procedure. Importantly, we were able to examine the functional relation between cue informativeness and temporal discrimination as a person learned the cue-interval correlation in each condition. Previous research has demonstrated that changes in cue informativeness may determine attention to the cue (Mackintosh, 1965) without disrupting temporal discrimination accuracy for the interval that occurred most frequently (Subramaniam and Kyonka, 2019). Analyzing changes in peak times, peak spread, and the shape of PI response distributions as participants learn to ignore the cues in the descending cue-informativeness condition and attend to the cues in the ascending cue-informativeness condition, should help disentangle underlying processes.

In Experiment 1, we found evidence consistent with each of Swanton et al.’s (2009) response strategies (e.g., averaging, either/or, cover both bases). Most PI response distributions were best described as Gaussian curves with a single peak and peak times in low cue-informativeness conditions fell between the peak times in the multiple schedule, providing evidence that participants averaged temporal memories. However, peak times fell closer to the long interval than the short interval, which supports an either/or strategy in which participants responded as if the long target was in effect. Peak spreads provided evidence that participants covered both bases. That is, participants responded throughout the PI trial as if they could earn points at either interval. Participants did not have much to lose by responding at a high rate in the short period of time between the two intervals, so peak spread may be a better indicator of underlying processes than peak time using this procedure.

In Experiment 2, we could test hypotheses about the structure of PI response distributions and how those distributions adjust with changes in cue informativeness. Fig. 4 is an illustrative example of predictions of the averaging, either-or, and cover-both-bases accounts on peak times for each cue-informativeness condition. If participants averaged the temporal intervals, single Gaussian functions would describe PI response distributions in all cue-informativeness conditions. We would also expect peak times and peak spreads in the mixed and intermediate schedule conditions (cue-interval $\phi < 1$) that equaled the average of peak times and spreads in the multiple schedule condition. As participants experienced each cue-informativeness condition, an averaging account predicted larger differences in short and long peak times for participants who received a descending than ascending order of cue-informativeness conditions. Finally, an averaging account predicted that peak times would change systematically in opposite directions for...
participants receiving cue-informativeness conditions in descending than ascending order.

If participants responded according to temporal biases using an either/or strategy, like the averaging strategy, single Gaussian functions would describe PI response distributions in all cue-informativeness conditions. For the either/or account, we expected peak times and spreads in mixed and intermediate schedule conditions that did not differ from those in the short or long background PI trials of the multiple schedule, depending on the direction of the bias. An either/or account also predicted no changes in peak times across mixed and intermediate schedule conditions, as PI response distributions would center around a single interval.

In contrast to averaging and either/or strategies, if participants covered both bases, PI response distributions would be determined by the momentary conditional probability of points. Peak times would be similar across all conditions. Bimodal Gaussian functions would describe the PI response distributions in each condition except the multiple schedule condition. With low cue-interval correlations, peak spreads would begin before the short target and end after the long target. In addition, differences in PI responding in different conditions would depend on the order in which participants experienced the different cue-interval correlations. Specifically, participants who experienced cue-interval correlations that were initially high and then decreased should use the background color to predict the target interval on PI trials at first but rely on it less with each subsequent condition. To cover both bases, PI response distributions should become more alike as a result. Participants who experienced the mixed, \( \phi = 0 \) condition first should learn that background color does not predict the target interval on PI trials. To cover both bases, PI response distributions in the first condition should be similar. Once that response pattern is established, there may be no reason for it to change.

5.1. Method

5.1.1. Participants

Six participants, three self-identified females (H2, H3, and H6) and three self-identified males (H1, H4, and H5), were recruited from psychology courses at a large Mid-Atlantic university. As in Experiment 1, participants were required to be at least 18 years old, have normal or corrected-to-normal binocular vision, and have avoided taking prescription or non-prescription drugs that affected their mood or energy levels. Participants earned research credit for every 30 min they spent in the laboratory and they participated for a chance to win a gift card valued at $50. All participants completed the four conditions of the experiment within one visit to the laboratory lasting less than 2 hrs.

5.1.2. Setting

Testing occurred in a 3 m x 2 m interior room in a laboratory. Participants sat at a desk containing one desktop computer with a monitor, keyboard, headphones, and mouse. Auditory stimuli were presented using a pair of stereo headphones. The color monitor presented visual stimuli using manufacturer-recommended display settings, and responses on the keyboard were recorded by the computer program. During experimental conditions, participants responded using the enter key and the spacebar key on the computer keyboard. The custom Microsoft Windows program, written in Microsoft Visual Basic © programming language, timed events with a 1-ms resolution, presented contingencies, and collected real-time experimental data.

5.2. Procedure

All study procedures were reviewed and approved by the University IRB and were carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki). When a participant arrived at the laboratory, the first author provided the participant with standard informed consent and asked that the participant put their belongings (including cell phones and watches) in a cubby outside the experimental room. The instructions, PI procedure, and cue-informativeness conditions were identical to Experiment 1. The only difference was that each participant received one session of each cue-informativeness condition.

To test all levels of cue informativeness and potential history effects of repeated exposure to cues, three participants (H1, H2, and H3) were given a descending order of cue-interval correlations: \( \phi = 1 \) condition first followed by the \( \phi = 0.8, 0.4, \) and 0 cue-informativeness conditions (high-to-low \( \phi \)). Three participants (H4, H5, and H6) were given an ascending order of cue-interval correlations: \( \phi = 0 \) condition first, followed by the \( \phi = 0.2, 0.4, \) and 1 cue-informativeness conditions (low-to-high \( \phi \)).

Each condition was in effect until we judged temporal discrimination to be stable. The stability criteria were no monotonic trends in single-trial measures of response-rate shifts (i.e., stop times, Church et al., 1994) during the last six PI trials of each color in the last block of a
session. Each condition was in effect for 120 trials (i.e., one session), and all participants met these criteria within one session. Participant H3 was exposed to 126 trials due to technical difficulties during the third session ($\phi = 0.4$). The researcher restarted the third session following 43 trials and the ended the fourth session following 83 trials.

6. Results

Figs. 5 and 6 show normalized rate of enter key presses as a function of time in the presence of the short and long background color PI trials, averaged across all PI trials in a session, in each cue-informativeness condition for individual participants. As in Experiment 1, response rate was normalized by dividing the PI trial duration into consecutive, 0.5-s bins, calculating the number of responses that occurred in each bin across all PI trials for that background, and dividing the response rate for each bin by the maximum binned response rate for that background color. Fig. 5 shows PI distributions for participants with descending cue-informativeness order (high-to-low $\phi$) and Fig. 6 shows PI distributions for participants with ascending cue-informativeness order (low-to-high $\phi$).

By visual inspection, response distributions were more similar when cue-interval correlations were low than when they were high. However, response distributions in the presence of short and long background colors were qualitatively more similar for participants who received ascending cue informativeness than for participants who received descending cue informativeness. Some distributions had visible evidence of multiple peaks, for example Participant H3 in the mixed schedule condition ($\phi = 0$), while others were unimodal, for example Participant H5 in the mixed schedule condition. To quantify these visual differences, curve fitting procedures described in Experiment 1 estimated peak times and peak spreads for each normalized PI response distribution. These procedures, along with NOP analysis, helped characterize the shape of response distributions to describe underlying learning processes.

6.1. Curve fitting and model comparison

Model comparison procedures were conducted as described in Experiment 1 to compare fits of single and summed Gaussian functions for PI response distributions for each participant, background color, and

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**Fig. 5.** Experiment 2 Normalized Peak Interval (PI) Response Rate Distributions (Descending Order). Note. Response rate in each 0.5-s bin was averaged across all light- or dark-green PI trials in each condition and expressed as the percentage of maximum rate (i.e., was normalized) for each participant experiencing descending cue informativeness (H1, H2, H3). Distributions are shown separately for the short (unfilled) and long (filled) background color (when $\phi = 1$). Dashed and solid lines are fits of the summed Gaussian model (Eq. 2). Each condition, labeled by phi ($\phi$) coefficient, is shown on a separate row.
The summed Gaussian function was a better fit than the single Gaussian for 27 out of 48 distributions (56.25%), indicating evidence of control by multiple intervals more often than not, and are shown as solid and dashed lines in Figs. 5 and 6.

Table 2 shows average peak time and spread for each participant in each condition using the best fitting model. If Eq. (1) was a better fit, the first and second peak time ($M_1$ and $M_2$) and spread ($SD_1$ and $SD_2$) were obtained from fits to response distributions across short-background PI trials (subscript 1) and long-background PI trials (subscript 2), respectively (light and dark green trials for $\phi = 1$). If Eq. (2) was a better fit, the first and second peak time and spread were an average of $M_1$s, $SD_1$s, $M_2$s and $SD_2$s from all PI trials. Peak times $M_1$ and $M_2$ were close to 2 s or 4 s in most conditions and peak spread $SD_1$ was generally smaller than peak spread $SD_2$.

Across all participants, background colors, and cue-informativeness conditions, first and second peak times (i.e., $M_1$ and $M_2$ in Eq. (2) or $M$ from the single Gaussian) were 2.76 s ($SE = 0.24$ s) and 3.74 s ($SE = 0.23$ s), respectively. A $2 \times 4 \times 2$ mixed ANOVA with first or second peak time and condition ($\phi = 1, 0.8, 0.4, 0$) as the within-subjects factors, and cue informativeness order as the between-subjects factor, found a significant difference between first and second peak times, $F(1,4) = 63.09, p < .01, \eta^2_p = 0.94$, and no other significant effects.

Across all participants, background colors, and cue-informativeness conditions, first and second peak spreads (i.e., $SD_1$ and $SD_2$) were 0.54 s (0.07 s) and 0.63 s (0.06 s), respectively. A $2 \times 4 \times 2$ mixed ANOVA with first or second peak spread and condition ($\phi = 1, 0.8, 0.4,$ or 0) as the within-subjects factors, and cue informativeness order as the between-subjects factor, found a significant difference between cue-informativeness order, $F(1,4) = 10.52, p < .001, \eta^2_p = 0.72$, with the ascending group having larger peak spreads ($M = 0.74$ s, $SE = 0.18$ s) than the descending group ($M = 0.43$ s, $SE = 0.08$ s). There were no other significant main effects and no significant interaction effects.

Compared to peak times, differences in peak spread were more variable, but there was no evidence that peak spread differed across first or second peaks, background, or levels of cue informativeness in a systematic way.

### 6.2. Quantifying differences in stimulus control by background color

Visual inspection of the PI distributions in Figs. 5 and 6 indicated that stimulus control by background color differed by condition; normalized...
was related to cue informativeness, then NOP should have been highest stimulus control that background color had over response distributions long intervals. Peak times occurred around the times of the short and cue-informativeness conditions (response distributions were under stimulus control by the short and/or the PI procedure. Consistent with Experiment 1, most participants using a within-subjects design. Each participant experienced all four ascending order of cue-informativeness conditions. If the degree of informativeness condition (and had response distributions that converged with decreasing informativeness had an average NOP of 0.60 responses (SE = 0.11 responses) and had response distributions that converged with decreasing informativeness, Friedman rank test, F(3) = 8.20, p = .04. Participants with ascending cue informativeness had an average NOP of 0.32 responses (SE = 0.08 responses) and their response distributions did not change with increasing informativeness, Friedman rank test, F(3) = 1.0, p = .80.

### 6.3. Discussion

Experiment 2 was conducted to characterize the relation between cue informativeness and temporal discrimination in human participants using a within-subjects design. Each participant experienced all four cue-informativeness conditions (ϕ = 1, ϕ = 0.8, ϕ = 0.4, or ϕ = 0) in the PI procedure. Consistent with Experiment 1, most participants’ PI response distributions were under stimulus control by the short and/or long intervals. Peak times occurred around the times of the short and long intervals. A bimodal curve was a superior fit to response distributions than a single Gaussian curve for a majority of PI response distributions. This result partially implied that participants, like pigeons in previous research (Subramaniam and Kyonka, 2019), used a cover-both-bases response strategy in the presence of mixed signals.

Also consistent with the cover-both-bases response strategy, adaptation of PI response patterns to changes in cue informativeness differed by cue-informativeness order. When cue informativeness was high, participants with descending cue-informativeness order responded earlier in short-background PI trials than they did in long-background PI trials. Those differences in response patterns decreased as cue informativeness decreased across conditions. In other words, short- and long-background PI response distributions failed to diverge across conditions. Similarly, peak spreads were larger for participants with ascending cue informativeness than those with descending cue informativeness. Taken together, the implication is that participants learned to ignore background color as it became less informative but they did not learn to attend to background color as it became more informative. These order effects were not observed in a previous study using a similar PI procedure with pigeons (Subramaniam and Kyonka, 2019). In that study, pigeons had extended exposure to experimental conditions. Pigeons in Subramaniam and Kyonka’s (2019) study completed at least 1600 trials per condition. In contrast, participants in this study were exposed to 120 trials per condition. Future research might determine whether PI response distributions diverge with increasing cue informativeness or whether peak times change when human participants have the same amount of exposure to each condition as nonhuman subjects.

The fact that participants with ascending cue informativeness had PI response distributions that did not adjust across conditions is consistent with theories of selective attention (Mackintosh, 1975; Sutherland and Mackintosh, 1971) suggesting that a learning rate parameter (alpha) or analyzer decreases in strength with each invalid presentation of a cue. In this study, we decreased cue informativeness using micsues, or presentations of cues that are correlated with multiple intervals. If micsues constituted invalid presentations of the background color, then at the end of each intermediate cue-informativeness condition, the learning rate parameter or analyzer should have been lower or weaker with ascending cue informativeness than descending cue informativeness. We would expect PI response distributions that are more converged in the former than they are diverged in the latter at the same cue-informativeness conditions.

These results have procedural and theoretical implications. Procedurally, if accurate temporal discrimination is a goal, it may not be

### Table 2

Experiment 2 Average Peak Time and Spread in Seconds.

| ϕ     | First Peak M1 (SE) | First Peak SD1 (SE) | Second Peak M2 (SE) | Second Peak SD2 (SE) |
|-------|--------------------|---------------------|---------------------|---------------------|
| Descending (high-to-low ϕ) |                     |                     |                     |                     |
| 1.0   | 2.45 (0.28)        | 0.44 (0.02)         | 3.56 (0.34)         | 0.56 (0.07)         |
| 0.8   | 2.30 (0.13)        | 0.37 (0.08)         | 3.27 (0.04)         | 0.42 (0.10)         |
| 0.4   | 2.19 (0.14)        | 0.30 (0.04)         | 3.31 (0.22)         | 0.59 (0.12)         |
| 0     | 2.18 (0.18)        | 0.30 (0.04)         | 3.44 (0.19)         | 0.49 (0.13)         |
| All   | 2.26 (0.09)        | 0.35 (0.03)         | 3.39 (0.10)         | 0.51 (0.05)         |
| Ascending (low-to-high ϕ) |                     |                     |                     |                     |
| 1.0   | 3.55 (1.09)        | 0.96 (0.29)         | 4.25 (1.15)         | 0.51 (0.14)         |
| 0.8   | 3.48 (1.22)        | 0.64 (0.19)         | 4.56 (1.24)         | 0.82 (0.15)         |
| 0.4   | 3.13 (1.04)        | 0.73 (0.24)         | 3.92 (0.84)         | 0.84 (0.15)         |
| 0     | 2.81 (0.46)        | 0.60 (0.13)         | 3.60 (0.69)         | 0.80 (0.14)         |
| All   | 2.34 (0.43)        | 0.74 (0.10)         | 4.08 (0.44)         | 0.74 (0.07)         |

Note. Peak times (M) and spreads (SD) were obtained from Eqs. (1 and 2). First and second peak times and spreads (subscripts 1 and 2, respectively) from the best-fitting model, parameters were first averaged within participants to obtain an average M1, SD1, M2, and SD2.

Fig. 7. Experiment 2 Nonoverlapping Portion (NOP) by Condition and Order. Note. Nonoverlapping portion (NOP) of short- and long-background PI trial response distributions, expressed as proportion, for each participant and cue-informativeness condition in Experiment 2. Bars are NOP averaged across participants in each cue-informativeness order group and markers are individual participants’ NOP.
worthwhile for researchers to try to teach humans to time multiple intervals with changing cue informativeness in a single laboratory visit. However, if there is limited training time, it may be better to begin training with high cue informativeness and decrease cue informativeness gradually rather than beginning training with low cue informativeness (i.e., use a descending cue-informativeness order). Theoretically, the non-averaging of temporal intervals by many research subjects in these experiments and most pigeons in a similar procedure (Subramaniam and Kyonka, 2019) are consistent with results of other temporal discrimination experiments in which subjects learn multiple intervals (e.g., De Corte and Matell, 2016; De Corte et al., 2018; Leak and Gibbon, 1995; Rakitin et al., 1998; Wearden and Lejeune, 2008, but e.g., Matell and Kurti, 2014, Swanton et al., 2011). Collectively, these empirical results support ‘non-averaging’ theories of temporal learning in which temporal memories for multiple durations are simultaneously encoded veridically (De Corte and Matell, 2016).

Most PI response distributions showed evidence of temporal discrimination by one or both intervals, but there were several individual differences in response patterns that should be noted. Closer inspection of the PI response distributions for participants with ascending cue-informativeness order suggests the presence of either/or, biased responding. Response distributions centered either around the short or the long interval. More precisely, peak times for ascending cue informativeness participants were either shorter than the harmonic mean of the short and long intervals (2.67 s) or longer than the arithmetic mean of the short and long intervals (3 s), with few exceptions. Peak times only indicated temporal control by the long interval for Participants H4 and H6, and temporal control by the short interval for Participant H5. There was evidence of temporal control by both intervals in many conditions for all three participants with descending cue informativeness. Participants with descending cue informativeness may have learned the intervals associated with each cue initially, then learned to respond at two time points in the presence of both background colors. Participants with ascending cue informativeness mostly responded at one time point in all conditions.

7. General discussion

People are often faced with mixed signals about the time to reinforcer availability and, in the presence of those signals, can respond using a variety of strategies. This study evaluated human temporal discrimination in a PI procedure in which we manipulated cue informativeness across groups (Experiment 1) or within subjects (Experiment 2). Cues predicted either a short or a long interval in a multiple schedule; preceded short and long intervals equally in a mixed schedule; and predicted short or long intervals most, but not all of the time, in schedules with intermediate cue informativeness. We expected that participants would average temporal information, use an either-or strategy, or cover both bases in the presence of mixed signals. There was mixed evidence of all response strategies in individual results; however, taken collectively, the results best supported the hypothesis that humans covered both bases.

Covering both bases by responding based on the momentary probability of reinforcement is a common result in research using mixed FI-FI schedules with short and long intervals (e.g., Leak and Gibbon, 1995; Whitaker et al., 2003, 2008). This research has reported that at the onset of the long FI, response rate is low, increases to a peak at the short interval, decreases to a low rate when the reinforcer is not delivered after that interval passes, and increases to a high rate until the reinforcer is delivered for the first response following the long interval elapsing. The same cover-both-bases pattern is best illustrated in PI response distributions in low cue-informativeness conditions (\( \phi = 0.4 \) and \( \phi = 0 \)) for H3 in Experiment 2. Although many PI response distributions in the current experiments were well-described by summed Gaussian functions, most participants did not exhibit H3’s M-shaped response pattern in PI trials. We might have observed more visibly bimodal distributions if the two programmed intervals had a larger absolute difference than 2 s. More time between the two intervals would have given participants the chance to stop responding and then resume again, given variability in temporal discrimination. A larger absolute difference between intervals would also be easier to discriminate than a smaller difference. Stimuli on the same continuum (e.g., intervals of time) are more discriminable when they are farther apart on the continuum (McLaren and Mackintosh, 2002).

Consistent with previous research validating the target game (Guilhardi et al., 2010) and research using a similar procedure with pigeons (Subramaniam and Kyonka, 2019), Experiments 1 and 2 found that relatively short intervals were discriminable to participants. All participants learned something about the time to point availability within one session of the PI procedure. Peak times were close to the programmed interval(s) and, for most participants, peak spreads were shorter for the short than long background color.

The current study found no significant differences in peak time and peak spread based on cue-informativeness condition; however, there was a difference in NOP across conditions. In causal detection research, participants usually match their predictions to the probability of an outcome given a cue (Beeley et al., 2015; Wasserman, 1990). PI response distributions shifted in similar ways in the current study. In Experiment 1, response distributions overlapped the most when cue informativeness was low and overlapped the least when cue informativeness was high. This same pattern was found for participants with descending cue informativeness order in Experiment 2. One interesting finding from Experiment 1 was that NOP at low cue-interval correlations (\( \phi = 0.4 \) and \( \phi = 0 \)) was statistically smaller than NOP at high cue-interval correlations (\( \phi = 0.8 \) and \( \phi = 1 \)). NOP did not differ between the two highest cue-interval correlations and between the two lowest cue-interval correlations. This finding implies that, at a certain low correlation, slightly predictive cues may have little value as signals and may function as a pure mixed schedule.

Adaptive changes in response patterns occurred across conditions between participants in Experiment 1 or within many participants in Experiment 2. Within one session, average normalized response rate increased from the beginning of PI trials to a peak and decreased before the trial elapsed. As in previous research (Sanabria and Oldenburg, 2014; Subramaniam and Kyonka, 2019; Whitaker et al., 2003, 2008), single and summed Gaussian functions characterized PI response distributions well.

Laboratory research with human participants investigating causal detection (e.g., Beeley et al., 2015; Wasserman, 1990), rule-governed insensitivity (Fox and Kyonka, 2017), and treatment integrity (e.g., Hirst et al., 2013; St. Peter Pipkin et al., 2010) has also produced order effects similar to those in Experiment 2 when cue-outcome correlations were manipulated. In general, participants learn to ignore cues that become uninformative when a cue-outcome correlation is initially high and decreases, but they do not learn to discriminate a previously uninformative cue. Invalid consequent events might affect response adaptation through similar attentional processes (e.g., Mackintosh, 1975) as misusing discriminative stimuli that signal fixed intervals.

Future research using the multiple cued PI procedure with pigeons and humans can be used to characterize other forms of invalid stimulus presentations to determine whether there are functional classes of cue informativeness. In skill-acquisition research, for example, reinforcers can be delivered incorrectly (e.g., DiGennaro Reed et al., 2011), instructions can vary in wording (e.g., Carroll et al., 2012), and feedback can be misleading (Hirst et al., 2013). Research on invalid consequent events such as incorrect feedback or point delivery (Hirst et al., 2013; St. Peter Pipkin et al., 2010) suggest that contingent, discrete mises might be functionally similar to the discriminative stimuli manipulated in the current investigation.

Other manipulations of cue informativeness can alter the signal-to-noise ratio (e.g., instructions varying in wording or length). When signals are noisy, cue-interval informativeness takes the form of variable-
interval schedules in which the time to reinforce availability varies along a distribution. Much like FI schedules, Catania and Reynolds (1968) described response rates in these VI schedules as dependent on the momentary conditional probability of reinforcement. If misuses and noise are functionally equivalent, then response distributions in PI trials following exposure to increasingly (or decreasingly) noisy intervals might converge when cue-interval correlations are low, as this experiment would suggest.

8. Conclusion

Cues, even with some degree of misinformation or noise, can tell people what to do and when to do it. Previous research has found that cue informativeness affects learning what to do (e.g., Beesley et al., 2015; Wasserman, 1990). The bull’s eye game used these experiments enabled us to ask whether cue informativeness affected responding, but also how it affected responding. Specifically, we asked whether participants would average temporal memories, use an either-or bias, or attempt to cover both bases. We found that momentary response rate in PI trials was mostly a function of the momentary conditional probability of points signaled by the background colors, which supported a cover-both-bases approach. Thus, what to do and when to do it are both affected by cue informativeness, but in different ways.

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