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PREFERENCE AS A FUNCTION OF ACTIVE INTERRESPONSE TIMES: A TEST OF THE ACTIVE TIME MODEL

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In this article, we describe a test of the active time model for concurrent variable interval (VI) choice. The active time model (ATM) suggests that the time since the most recent response is one of the variables controlling choice in concurrent VI VI schedules of reinforcement. In our experiment, pigeons were trained in a multiple concurrent similar to that employed by Belke (1992), with VI 20-s and VI 40-s schedules in one component, and VI 40-s and VI 80-s schedules in the other component. However, rather than use a free-operant design, we used a discrete-trial procedure that restricted interresponse times to a range of 0.5–9.0 s. After 45 sessions of training, unreinforced probe periods were mixed with reinforced training periods. These probes paired the two stimuli associated with the VI 40-s schedules. Further, the probes were defined such that during their occurrence, interresponse times were either ''short'' (0.5–3.0 s) or ''long'' (7.5–9.0 s). All pigeons showed a preference for the stimulus associated with the relatively rich VI 40-s schedule—a result mirroring that of Belke. We also observed, though, that this preference was more extreme during long probes than during short probes—a result predicted by ATM.

Key words: interresponse times, active time model, stay/switch model, Belke (1992), variable-intervals, pigeons

This experiment tested the hypothesis that choice under concurrent variable-interval (VI) VI schedules of reinforcement is controlled by the time since the most recent response. This time variable has been termed ''active time,'' and the model describing its relevance to choice behavior has been designated the active time model, or ATM (Cleaveland, 1999). ATM is a stochastic, molecular model that successfully describes a range of choice behavior for pigeons responding on concurrent VI VI schedules of reinforcement (Brown & Cleaveland, 2009; Cleaveland 1999, 2008; McKenzie & Cleaveland, 2010). The model assumes that during training pigeons learn a function that relates active times to switches and stays into and out of choice ''states.'' With its emphasis on interresponse times and switches versus stays, ATM falls within a broad theoretical approach to choice behavior that is shared by models such as momentary maximization (Shimp, 1969) and the stay/switch model (MacDonall, 2009). Our test of ATM uses a discrete-trial multiple concurrent VI VI procedure. However, before describing our test in detail, we will first describe how ATM emerges from the moment-to-moment contingencies arranged by concurrent VI VI schedules.

Theoretical Framework

Concurrent VI VI reinforcement schedules are usually arranged in the laboratory so that reinforcers occur at an average fixed rate and with a constant overall probability. This is accomplished by using an exponential distribution, as given in Equation 1 and frequently approximated with a procedure outlined by Fleshler and Hoffman (1962).

$$P_i = 1 - e^{-(t_i/\lambda_i)} \qquad (1)$$

Equation 1 shows that P_i, the momentary probability of reinforcement at Choice *I*, changes as a function of the time, t_i, since last choosing Choice *i* and the average reinforcement interval, λ_i, assigned to Choice *i*. The contingencies of reinforcement for a VI schedule, then, explicitly target t_i, the interesponse time (IRT) that separates choices at a particular schedule. In concurrent VI VI schedules every choice can be defined in relation to two such IRTs: *active time* and *background time* (Cleaveland, 1999). Active time corresponds to the time since the most recent schedule choice, while background time refers to the time since the alternative schedule was chosen.

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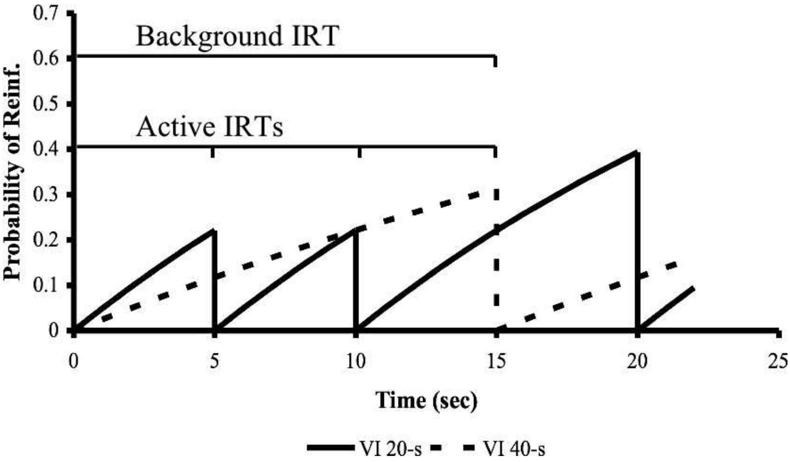

Fig. 1. Active and background interresponse times. The figure assumes that a subject responds once every 5 s, and shows the relationship between interresponse times (IRTs) and reinforcement probabilities programmed according to Equation 1. In this case, the subject is shown to make two responses to the VI 20-s schedule, one response to the VI 40-s schedule, before switching back to the VI 20-s schedule. Notice that choosing an alternative immediately resets its probability of reinforcement to 0. Further, the figure highlights two types of IRT: active and background. As the subject responds, the time since the last peck to the alternative schedule, that is, the background IRT, increases. Conversely, the active IRT is defined as the time since the most recent choice, regardless of the alternative selected.

Figure 1 illustrates our two classes of IRT for concurrent VI 20-s VI 40-s schedules, and, using Equation 1, relates them to reinforcement probabilities. For simplicity, Figure 1 assumes a response every 5 s. As can be seen, reinforcement probabilities reset at an alternative with every response to that alternative. After a reset, reinforcement probabilities negatively accelerate as a function of active time for the most immediately selected alternative, and as a function of background time for the non-selected alternative.

Given Figure 1, one might reasonably conclude that organisms will discriminate among active and background times so as to choose whichever alternative had the momentarily higher probability of reinforcement. This hypothesis is termed momentary maximizing, and it does have some support (e.g., Hinson & Staddon; 1983a, 1983b; Silberberg, Hamilton, Ziriax, & Casey, 1978). However, a consistent finding in the literature is that animals do not become more likely to switch from an alternative as background time increases (Cleaveland, 1999; Heyman, 1979; Nevin, 1969). This failure to discriminate among changes in background times, however, should not come as a surprise. A concurrent VI VI procedure presents a complex interval timing structure. Background and active IRTs do not start in parallel, and while the background IRT is accumulating, the active IRT might accumulate and reset several times. Also, the trigger initiating each IRT is not an external event, but a behavior that is common to both intervals (i.e., a key peck). Given this complexity, ATM proposes that temporal control during concurrent VI VI schedules is restricted to active IRTs. In this sense ATM is a constrained version of momentary maximizing.

If choice is controlled by a single, momentary temporal variable, however, then by necessity the relevant operants for ATM become switches and stays, rather than the selection of programmed reinforcement schedules per se. This is a viewpoint shared by MacDonall's stay/switch model (MacDonall, 2000, 2003, 2009). In experiments with rats MacDonall has shown that ''stays'' and ''switches'' are allocated at molar levels so as to maximize the reinforcement probabilities for each of these classes of behavior. ATM adds a dynamic variable to this framework. That is, ATM claims that it is not just stays and switches that are reinforced but rather stays and switches at particular times.

Figure 2, taken from Cleaveland (1999), shows how stay and switch responses are, in fact, mediated by active IRTs during concur-

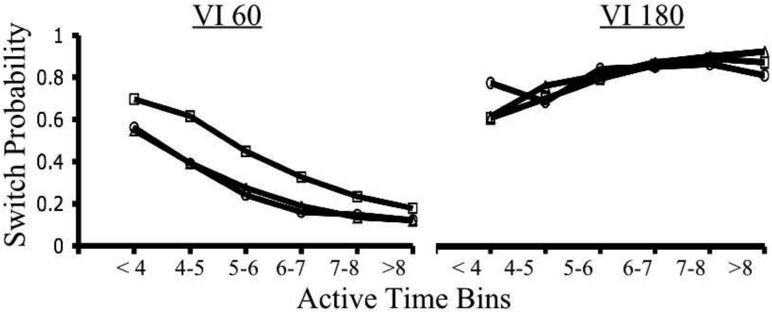

Fig. 2. Active time functions for 3 subjects. The data shown here is taken from Cleaveland (1999), and shows the behavior of 3 pigeons in a discrete-trial, concurrent VI 60-s VI 180-s schedule of reinforcement. Both plots provide the probability of switching from a schedule given increasing, active IRTs. Plots on the left are for cases in which the most recent response was to the VI 60-s schedule, while the plots on the right are for cases in which the most recent response was to the VI 180-s schedule. Note that when the most recent response was to the relatively rich, VI 60-s schedule, birds were more likely to select the VI 60-s schedule again as active IRTs increased. In contrast, when the most recent response was to the relatively lean, VI 180-s schedule, birds were more likely to switch away from the VI 180-s schedule as active IRTs increased.

rent VI VI schedules. The switch functions are from 3 birds that were trained under concurrent VI 60-s VI 180-s schedules. The left-hand plots show the probability of a switching out of the VI 60-s schedule given changes in the active IRT. All of the subjects showed higher switch probabilities at shorter than longer active times. The right-hand plots show a different result. They provide switch probabilities from the relatively lean, VI 180-s schedule, and show that birds tended to increase switch probabilities as a function of active time.

Testing Active IRT Control

ATM, then, suggests that during concurrent VI VI procedures, birds come to pattern their stay and switch responses depending upon the active IRT. To test this hypothesis, the following experiment utilizes a procedure similar to Belke's (1992) experiments. In Belke's experiment, pigeons were trained under multiple concurrent VI VI schedules. Specifically, the birds experienced periods of a concurrent VI 20-s VI 40-s schedule intermixed with periods of a concurrent VI 40-s VI 80-s schedule. Within pairings, Belke observed that his subjects' choice behavior conformed to the well known matching law (Herrnstein, 1961). That is, during training, his subjects approximated a 2:1 preference for the relatively richer schedule of a given pairing. After training, Belke intermixed unreinforced probe periods and reinforced normal periods. Probes paired stimuli associated with the two VI 40-s schedules, while normal periods continued the trained VI VI pairings. We will use a subscript to indicate the schedule with which a probe stimulus was trained. Belke observed that all of the birds showed a strong preference for the VI 40_{80} stimulus when it was paired with the VI 40_{20} stimulus. This result, since replicated (Gibbon, 1995; Williams & Bell, 1996), invalidates several choice models (see Williams, 1994).

Cleaveland (2008) pointed out that ATM, in principle, predicts a choice bias in the same direction as that observed by Belke (1992) in his probes. If the switching functions shown in Figure 2 are associated with discriminative stimuli, then Belke's probes essentially pair a ''rich'' switch function with one that is ''lean.'' Such a pairing would cause a subject to switch more often from the VI 40_{20} stimulus than from the VI 40_{80} stimulus. McKenzie and Cleaveland (2010) tested this hypothesis in a procedure similar to Belke's, and found that the observed switch functions could be used to accurately model the individual preferences obtained during probes. The following experiment extends the work of McKenzie and Cleaveland by noting that the functions in Figure 2 make a novel prediction. Namely, if ATM is correct, and functions such as those shown in Figure 2 determine choice, then it should be possible to control the preferences shown by pigeons during probes by controlling active time. This prediction is illustrated in Figure 3.

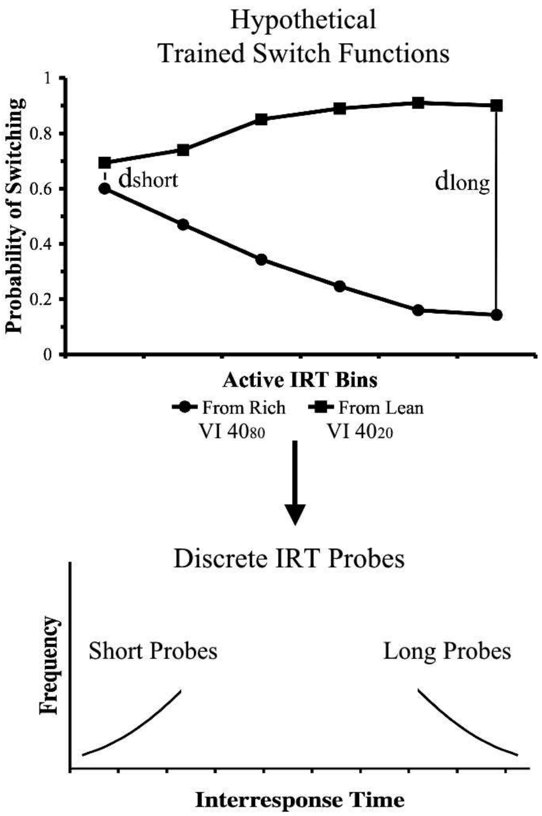

Fig. 3. Our predictions are based on the assumption that pigeons learn typical rich versus lean, active IRT switch functions. As noted in the text, after responding to a relatively rich VI schedule pigeons have been found to be more likely to switch after shorter than longer active IRTs. Conversely, after responding to a relatively lean VI schedule, pigeons usually show a high probability of switching across all active IRTs. In other words, at short active IRTs the difference between switching probabilities (d_{short}) for the relatively lean and rich schedules would be small in comparison to switch probabilities after long IRTs (d_{long}). If switch probabilities determine overall preference at suggested by the active time model (ATM), then we would predict that pigeons would show more extreme schedule preferences after long active IRTs than after short active IRTs. Our experiment tests this hypothesis via probe trials in which a restricted portion of IRTs are allowed, and pigeons are given a choice between stimuli previously paired with a relatively rich VI 40-s stimulus (VI 40_{80}) and a relatively lean VI 40-s schedule (VI 40_{20}).

In the following experiment pigeons were trained under multiple concurrent VI 20-s VI 40-s pairings and VI 40-s VI 80-s pairings. However, rather than utilize a free-operant procedure, we used a discrete-trial procedure. In a discrete-trial procedure, IRTs are under experimental control. In our case, IRTs were allowed to range from 0.5–9.5 s according to a Gaussian function with a mean of 5 s. After training, we exposed our birds to two types of probes: short and long. Short probes were restricted to IRTs of 0.5–3.0 s, while long probes were restricted to IRTs of 7.0–9.5 s. We predicted that if active IRTs mediate switch-and-stay responses, then preference during short probes would be less extreme than preference during long probes. This follows from the hypothetical functions shown in Figure 3. In Figure 3 the difference between rich and lean switch probabilities is less extreme at shorter than at longer active times. To our knowledge, our prediction that active time will influence preference during probes is unique to ATM. No other extant model of behavior under concurrent VI VI schedules of reinforcement makes such a prediction.

METHOD

Subjects

Five adult white Carneaux pigeons were used as subjects. The birds were housed in individual cages (40 cm × 40 cm × 40 cm) located in a well-ventilated, brightly lit room with a 12:12 h light/dark cycle. The birds were kept at 85% of their free-feeding weights for the duration of the experiment, and had access to water and grit while in their cages. Food consisted of mixed grains in the experimental chamber and Purina pigeon chow mixed with mixed grains when in the home-room. On days in which subjects underwent an experimental session (5 - 6 times per week), their only access to food was the reinforcement received during the session. This experiment conformed to practices outlined in the Guide for the Care and Use of Animals.

Apparatus

Experimental sessions took place in a 36-cm × 34-cm × 34-cm stainless steel operant box (32 × 34 × 34 with grid flooring inserted) located in a dimly lit room. A Plexiglas clasp door allowed access into the interior of the box. Opposite this door was a panel with three translucent pecking keys, a small 24-V light bulb, and a hopper that allowed access to grain during reinforcement. The hopper was located at the vertical median of the panel, 8 cm from the grid floor, and was 2 cm in diameter. There was also a white 24-V light bulb 16 cm from the top of the box and directly above the hopper, which was illuminated during the delivery of reinforcement. The three pecking keys were equally spaced from each other, 7.25 cm apart, 7 cm from the top, and 6 cm from the nearest side-edge to the left and right. The diameter of each key was 2.6 cm. Stimuli were projected on to the back of the pecking keys by means colored 24-V light bulbs mounted behind the keys.

Procedure

Training sessions. All birds experienced 45 sessions of multiple concurrent VI VI schedules with each bird being run 5-6 days per week. Schedule pairs consisted of VI 20-s VI 40-s and VI 40-s VI 80-s schedules with reinforcement at each schedule programmed according to Equation 1. Schedules were arranged across the three keys such that the right and left keys were only associated with the VI 40-s schedules. The center key was associated with either the VI 20-s or VI 80-s schedule, depending on the schedule pairing. In addition, each individual schedule was associated with a white, red, green, or blue color that was projected onto the back of the keys. One of the VI 40-s schedules was paired with a white stimulus on the leftmost key; the other VI 40-s schedule was paired with a blue stimulus on the rightmost key. The VI 20-s and VI 80-s schedules were paired with either a red or a green stimulus, with 2 birds experiencing one pairing and 3 experiencing the other. Reinforcement consisted of 1.8 s of access to food from the hopper. During the reinforcement period, the light above the hopper was illuminated.

Each training session consisted of twenty 120-s choice periods separated by 15-s timeouts in which all of the key lights were extinguished. During a choice period, one of the two pairs of concurrent VI VI schedules was randomly selected and the appropriate key lights illuminated. Subjects were permitted 2 s to peck either of the illuminated keys. After a response, after a response followed by reinforcement, or after 2 s without a response, the key lights were extinguished for an interresponse interval. This interval was determined by a Gaussian distribution with a mean of 5 s and a variance of 2. Intervals were further constrained to a range of 0.5-9.5 s by resampling the Gaussian distribution if an interval fell outside of this range. If the subject responded during the interresponse interval, then the timer for the interval was reset. At the end of an interval, that choice period's schedule keys were reilluminated, and the subject was permitted another choice.

As noted, reinforcers were programmed according to Equation 1. In other words, and in contrast with many other procedures, reinforcers were never ''held'' for a subject either within a 120-s choice period, or between periods. Rather, the amount of time that had passed since an alternative was last chosen (t_i in equation 1) directly determined the probability of reinforcement for that particular choice. These times were always set to 0 for both alternatives at the start of a 120-s choice period. During the reinforcement of an alternative, the IRT for that alternative did not accrue, and remained at 0 for the duration of the reinforcer delivery. However, the IRT for the nonreinforced alternative continued to accrue for the duration of a reinforcer delivery.

Probe sessions. After 45 training sessions, probe sessions were introduced. A total of four probe sessions were administered. Between probe sessions, each subject underwent three training sessions as outlined above.

Each probe session consisted of thirty 120-s choice periods. Twenty of these periods were the same as the previously trained multiple concurrent VI VI schedules, while 10 were probe periods during which no reinforcement was delivered. Probe periods consisted of pairings of the illumination of the schedule keys used for the two VI 40-s schedules (i.e., the leftmost and rightmost keys).

Two types of probe periods were defined. These types were characterized by the length of the interresponse intervals. Short probes restricted interresponse intervals to 0.5 -3.0 s; long probes restricted interresponse intervals to 7.0-9.5 s. These intervals were drawn from the same Gaussian function that defined the training intervals, but restricted to the desired range. In an attempt to control for unequal extinction effects, long probe periods were programmed to occur with approximately twice the frequency of short probe periods. Of the 40 total probes periods experienced by each subject, 13 were short probes, while 27 were long probes. Within a probe session, probe types were selected randomly from a predetermined list. However, probe periods

Table 1

Comparision of Choice Proportions Using Obtained Data and Simulations of ATM.

		Training	
	Subject	Obtained Data	ATM Simulations
	6	0.82	0.83
	7	0.73	0.66
VI 20 VI 40	8	0.70	0.71
	9	0.61	0.64
	10	0.74	0.82
	Average	**0.72**	**0.73**
	6	0.65	0.68
	7	0.74	0.73
VI 40 VI 80	8	0.65	0.57
	9	0.62	0.63
	10	0.56	0.53
	Average	**0.64**	**0.63**

		Probes	
	Subject	Obtained Data	ATM Simulations
	6	0.65	0.42
	7	0.53	0.47
Short	8	0.48	0.51
	9	0.50	0.44
	10	0.58	0.59
	Average	**0.55**	**0.49**
	6	0.84	0.72
	7	0.73	0.77
Long	8	0.65	0.62
	9	0.62	0.58
	10	0.70	0.64
	Average	**0.71**	**0.67**

Note. In all cases, the data provided indicate the degree of preference for the relatively rich schedule or stimulus. Simulations utilized the programmed Gaussian IRT function and the switch functions provided in Figures 4 and 7.

and training periods were intermixed such that probes were always separated by at least one, but no more than three, training period(s).

RESULTS

Overall choice proportions were calculated for each schedule pairing across the last 15 sessions of training (see Table 1). For the relatively rich schedule these proportions ranged from .64–.83 in the VI 20-s VI 40-s pairing (mean = .73, *sd* = .08), while in the VI 40-s VI 80-s pairing choice proportions ranged from .56–.74 (mean = .64, *sd* = .07). As a group the pigeons conformed reasonably well to a 2 :1 preference for the relatively rich schedule, although individual birds did show undermatching and overmatching (Baum, 1974, 1979). Further, despite differences in the group averages, a two-tailed *t*-test did not reveal a significant difference between overall choice proportions for the two schedule pairings, $t(4) = 1.6$, $p = .15$.

Figure 4 provides the proportion of switches for each subject within binned active times drawn from the .5–9.5 s range defined by our Gaussian function. Bins sizes had a range of 1 s except for the longest and shortest bins, which collected active times over a range of 2.5 s (i.e. from .5–3.0 s and from 7.0–9.5 s). Proportions were calculated over the last 15 sessions of training and were not considered valid unless the total responses collected for a bin were greater than 20. Plots on the left provide switch proportions out of the relatively rich alternative, while plots on the right provide the switch proportions out of the lean alternative.

Figure 4 shows that switch proportions varied as a function of the active schedule IRT. All birds were more likely to switch from the relatively rich alternative after a short IRT than after a long. After active times of .5–3.0 s, for example, Bird 6 was three times more likely to emit a switch than a stay when in the VI 40_{80}-s schedule. After times of 7.0–9.5 s, though, this same bird was three times more likely to emit a stay than a switch when in the same schedule. In contrast, switching out of the relatively lean schedules either increased in frequency or remained relatively flat as a function of active IRT duration. Bird 6 was about equally likely to switch or stay from the VI 80_{40}-s schedule during the shortest bin intervals. At the longest bin interval, this same pigeon was approximately twice as likely to switch.

Figure 4 illustrates that the differences between relatively rich and lean functions were more pronounced at longer than at shorter active times. Figure 5 examines this pattern in more detail by considering the difference between the switching functions for the two VI 40-s schedules (i.e., the relatively rich VI 40_{80} and the relatively lean VI 40_{20}). For simplicity only differences at the shortest and longest time bin are considered. Figure 5 clearly shows that the difference between these two active time functions was greater at the longest time bin than at the shortest time bin.

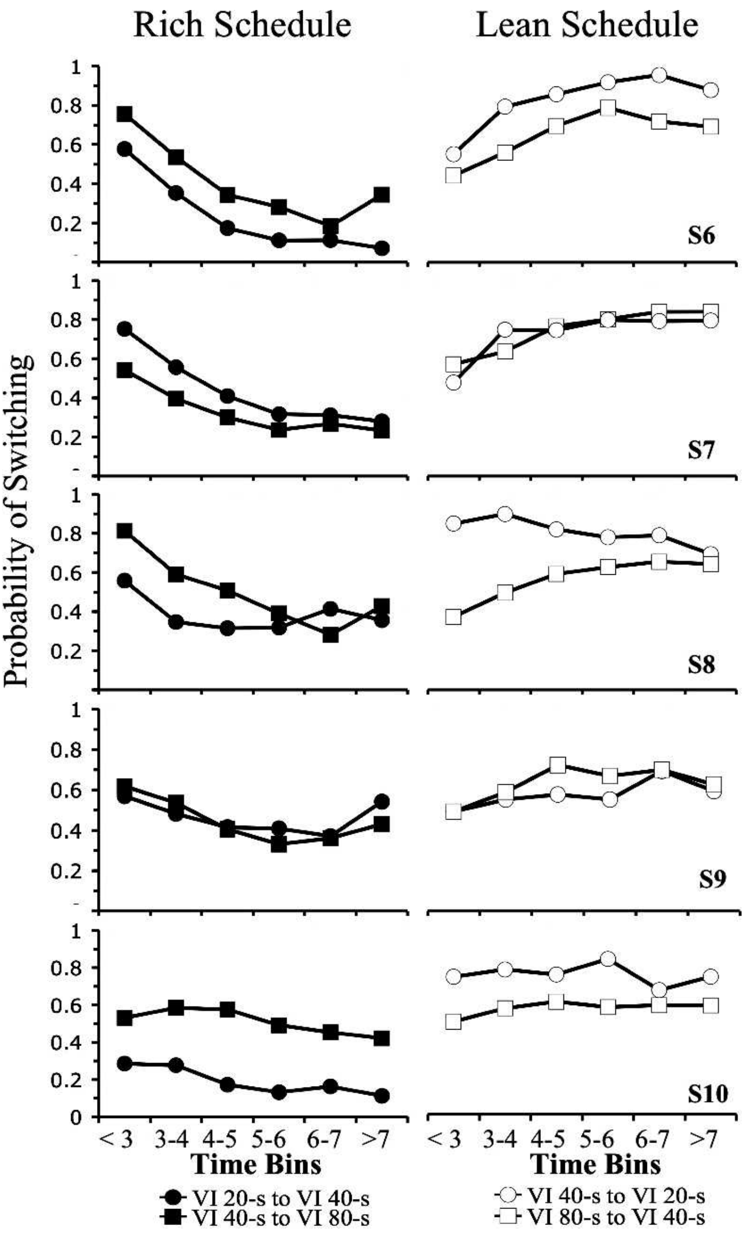

Fig. 4. Functions showing the probability of a switch given different active IRT bins during the last 15 sessions of multiple concurrent VI VI training. Time bins ranged from IRTs less than 3 s to IRTs greater than 7 s. From top to bottom plots are for Birds 6-10, respectively. Plots in the left column (filled symbols) indicate cases in which the most recent response was to the relatively rich schedule of a concurrent pair. Plots in the right column (empty symbols) indicate cases in which the most recent response was to the relatively lean schedule of a concurrent pair. Circles specify the VI 20-s VI 40-s pair, while squares specify the VI 40-s VI 80-s pair.

Within a range of .5–3.0 s, the probability differences ranged from −.20 to .22 (mean = .09). For the two longest bins, probability differences ranged from .16 to .56 (mean = .43). The stimuli associated with these reinforcement schedules were, of course, not paired during training. However, comparing these active time functions allows us to make predictions for our probes. For example, when the difference is negative (i.e., proportion of

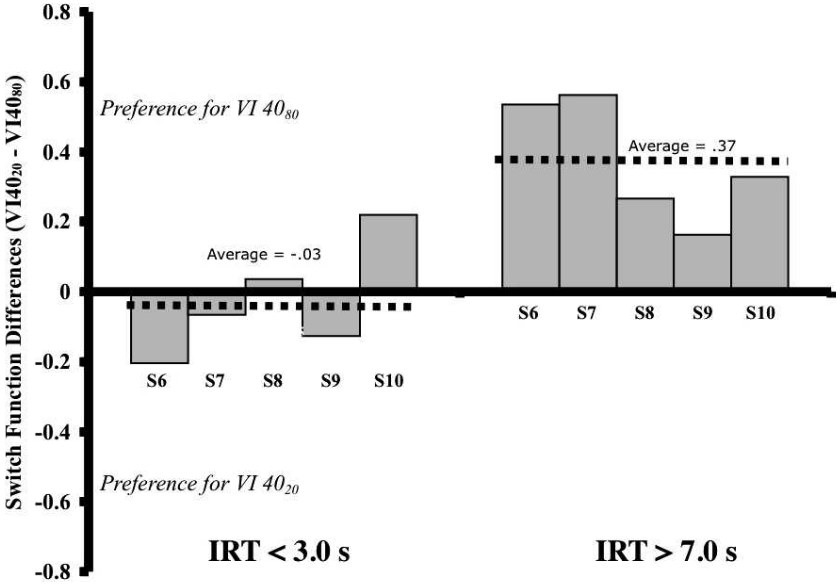

Fig. 5. Differences between the switch functions provided in Figure 4. Specifically, the figure shows the difference between the relatively rich VI 40_{80} and the relatively lean VI 40_{20} functions and the shortest and longest active IRT time bins. Bars left to right indicate Birds 6–10, respectively. The function differences permit a qualitative prediction of ATM for probe tests that will pair the stimuli associated with the VI 40-s schedules (see Figure 3). ATM predicts that small differences would correspond to indifference during probe tests. Negative values correspond to preference for the VI 40_{20} stimulus, while positive values correspond to preference for the VI 40_{80} stimulus. Thus, Figure 5 leads to the prediction that our Long probes will produce a much greater preference for the VI 40_{80} stimulus than will be shown during our Short probes.

switches out of VI 40_{80} > the proportion out of VI 40_{20}), then ATM predicts a preference for the relatively lean VI 40_{20} stimulus. Conversely a positive result would lead to the prediction of a preference for the relatively rich VI 40_{80} stimulus. Taken together, Figure 5 leads to the prediction that Long probes (IRTs ranging 7.0–9.5 s) will produce more extreme preference for the VI 40_{80} stimulus than Short probes (IRTs ranging .5–3.0 s). Such a prediction is borne out in Figure 6.

Figure 6 presents the proportion of responses made to the VI 40_{80} stimulus during Short and Long probes. This data shows that during Long probes subjects preferred the VI 40_{80} stimulus (mean = .71, *sd* = .08) to a much greater degree than during Short probes (mean = .55, *sd* = .07). This was true of every subject, and a one-way paired *t*-test of the data found the result to be significant, $t(4) = -3.27$, $p < .001$.

To more tightly link the switch functions shown in Figure 4 and the choice proportions shown by our subjects, Monte Carlo simulations of training and of the probe tests were conducted for each subject. These simulations consisted of two parts. First, an IRT generator determined when a response would occur. This generator was simply defined by the same Gaussian function used in our experiment for determining discrete-trial intervals. For training simulations, the range of IRTs was .5–9.5 s. For the probe simulations the range was set at .5–3.0 s for Short probes and at 7.0–9.5 s for Long probes. After determining when a response would occur, the appropriate switch function given in Figure 4 was used to determine whether this number resulted in a switch or stay response. Simulations ran for a total of 5,000 responses each, and the results are shown in Table 1.

In terms of the schedule preferences obtained during the last 15 sessions of training, simulated preferences were statistically indistinguishable from the actual, obtained data. Further, the simulated data approximated the rank order observed in the actual data. During VI 20-s VI 40-s training, Subject 6 produced the most extreme preference, while Subject 9 produced the least extreme preference. Simi-

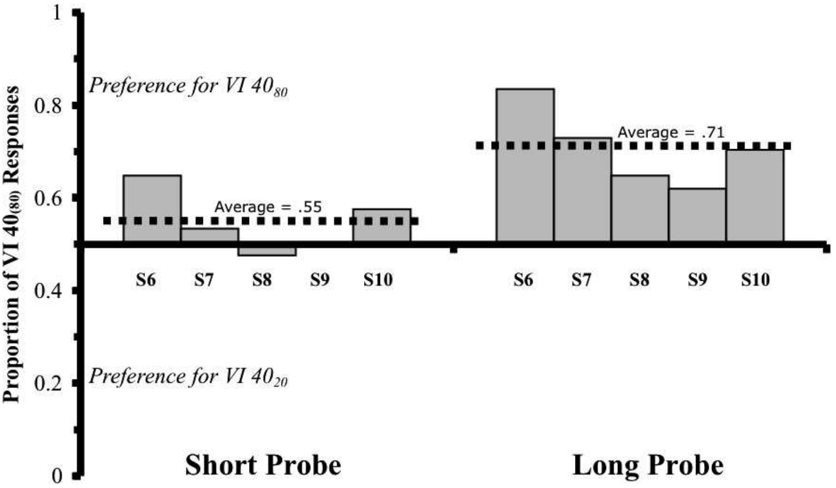

Fig. 6. Obtained probe preferences. The bar plots provide the proportion of responses made to the VI 40_{80} stimulus during Short and Long probe intervals. Bars left to right indicate Birds 6–10, respectively. Note that the x-axis crosses at 0.5, which would correspond to an equal number of responses being made to the VI 40_{80} and the VI 40_{20} stimuli (i.e., indifference). Therefore, proportions less than 0.5 indicate preference for the VI 40_{20} stimulus, while proportions greater than .5 indicate a preference for the VI 40_{80} stimulus. As predicted by ATM, Figure 6 shows that preference for the VI 40_{80} stimulus became more extreme during Long probe intervals as compared with Short probe intervals.

larly, during VI 40-s VI 80-s training, Subjects 7 and 10 were the ''high'' and ''low'' subjects, respectively, in terms of both obtained. Our simulations generated similar rankings. More importantly, though, our simulations mirrored the results obtained from our probe tests. As can be seen in Table 1, simulations of the VI 40_{20} VI 40_{80} probes produced less extreme preferences during Short probes than during Long probes (.49 and .65, respectively, in favor of the VI 40_{80}). That is, using switch functions obtained from the end of training allowed for predictive simulations of novel stimulus combinations for individual subjects.

Finally, recall that our procedure biased probe presentations by 2:1 in favor of the Long probes. This was done in order to account for the greater overall responding permitted during Short probes. Since all probe trials were 120 s in duration, it follows that more responding would occur in any given Short probe, when IRTs were restricted to .5–3.0 s, than in any given Long probe, when IRTs were restricted to 7.0–9.5 s. Given our 2:1 bias in probe presentations we obtained the following response totals. For subjects 9 and 10, the total number of responses during short and long probe sessions was approximately equal (252 vs. 240 and 285 vs. 287, respectively). Subjects 6 and 7 made more responses during short probe sessions than during long probe sessions (392 vs. 273; 264 vs. 196, respectively), while Subject 8 responded more during long probe sessions (109 vs. 142).

DISCUSSION

Our experiment tested the hypothesis that choice under concurrent VI VI schedules is partially determined by the time since the most recent response. This variable has been termed ''active time'' and lies at the core of a model termed the active time model, or ATM (Cleaveland, 1999, 2008). To test this hypothesis, pigeons were trained with a discrete-trial procedure under multiple concurrent VI 20-s VI 40-s and VI 40-s VI 80-s schedules. At the end of this training, all of our birds showed regularities relating active time to choice behavior (Figures 4 and 5), and these regularities allowed us to make predictions regarding preference during novel stimulus pairings. These pairings consisted of unreinforced probes that paired the two VI 40-s stimuli in a manner similar to Belke (1992). Our prediction, drawn from the active time functions given in Figure 4, was that choice for the VI 40_{80} stimulus would be positively correlated with active IRTs. This prediction was borne out. Birds chose the VI 40_{80} stimulus over the

VI 40_{20} stimulus significantly more often during long, as opposed to during short, probes (Figure 6). To our knowledge, ATM is the only choice model that makes this prediction.

It must be noted, though, that the data in support of ATM are but a late addition to a growing set of findings suggesting that subjects learn patterns of stay-and-switch responses during concurrent schedules of reinforcement. Indeed, some of the earliest support for momentary maximization models of choice (e.g., Shimp, 1966, 1969) came from findings of response patterns during concurrent VI VI schedules. For example, assuming that a subject responds at a constant rate, concurrent VI VI schedules yield the greatest probability of reinforcement at each response if the emitted response sequence is equivalent to the ratio of the schedule values. Figure 1 illustrates this fact. For a VI 20-s VI 40-s schedule, the optimal response sequence consists of two responses to the VI 20, followed by a single response to the VI 40. In fact, pigeons do approximate the optimal response sequence when responding under concurrent VI VI schedules of reinforcement (Silberberg et al., 1978).

However, the learned patterns of responding suggested by momentary maximization are assumed to emerge from a comparison of the relative value (in terms of momentary reinforcement probabilities) of the concurrent schedules of reinforcement. In contrast, more recent results indicate that learned patterns of responding are to some degree independent of the relative value of the underlying schedules of reinforcement (Gibbon, 1995; McDevitt & Bell, 2008; Williams & Bell, 1996). For instance, Williams and Bell conducted an experiment that utilized multiple, concurrent VI 20-s VI 40-s and VI 40-s VI 80-s schedules of reinforcement just as used by Belke (1992) and in the current study. However, their procedure signaled the arrival of reinforcers at the VI 20-s schedule. Such signaling caused the birds to spend considerably more time responding at the VI 40_{20} stimulus during training. In probes that paired the VI 40_{20} and VI 40_{80} stimuli, Williams and Bell found that their subjects preferred the VI 40_{20} stimulus. In other words, it appeared that stay-and-switch patterns established during training determined the probe results.

In terms of theory, the sequential dependencies observed under concurrent schedules of reinforcement have led some to focus on whether the appropriate response unit in such schedules is simply ''choices of VI_x or VI_y''. For example, Machado (1992) used frequency-dependent schedules, of which concurrent VIs are a subset, that differentially reinforced relative choice frequencies. What he found was that when response units were defined in terms of a single stay or switch, pigeons quickly learned to maximize reinforcement by alternating L (left) and R (right) pecks. Further, when response units were defined in terms of two responses—LL, LR, RL and RR—some of the pigeons learned to maximize reinforcement by emitting each pair once, in sequence (e.g., RRLLRLLR). Similarly, MacDonall's stay/switch model (MacDonall, 2000, 2003, 2009) is a molar model of choice in which stays and switches are the reinforced response units. In experiments with rats MacDonall has shown that stays and switches appear to be allocated at molar levels so as to maximize the reinforcement probabilities for each of these classes of behavior.

Our results reported in this article, then, comfortably fit with a broad range of data. Animals appear to learn patterns of responding under concurrent schedules of reinforcement, and these patterns are at least partially independent of the absolute value of the underlying schedules. Our contribution is to show that such patterns of responding have a temporal component determined by the active IRT. Under concurrent VI VI schedules of reinforcement, our subjects showed switch patterns that correlated with active IRTs. Further, we found that these switch patterns carried over to unreinforced probe trials that utilized novel stimulus combinations. Future work, therefore, will need to focus on the origins of active IRT switch functions under concurrent schedules of reinforcement.

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