

Learning in the Temporal Bisection Task: Relative or Absolute?

Marília Pinheiro de Carvalho
and Armando Machado
University of Minho

François Tonneau
Federal University of Pará

We examined whether temporal learning in a bisection task is absolute or relational. Eight pigeons learned to choose a red key after a *t*-seconds sample and a green key after a 3*t*-seconds sample. To determine whether they had learned a relative mapping (short→Red, long→Green) or an absolute mapping (*t*-seconds→Red, 3*t*-seconds→Green), the pigeons then learned a series of new discriminations in which either the relative or the absolute mapping was maintained. Results showed that the generalization gradient obtained at the end of a discrimination predicted the pattern of choices made during the first session of a new discrimination. Moreover, most acquisition curves and generalization gradients were consistent with the predictions of the learning-to-time model, a Spencean model that instantiates absolute learning with temporal generalization. In the bisection task, the basis of temporal discrimination seems to be absolute, not relational.

Keywords: relational versus absolute, generalization gradients, temporal bisection, learning-to-time (LeT) model, pigeons

Gestalt psychologist Wolfgang Köhler proposed that animals are able to respond to relations between stimuli. In one study, Köhler (1918/1938) gave chickens a choice between a bright gray and a dark gray rectangle, and reinforced choosing bright gray. Afterward, given a choice between the reinforced bright gray and a new, brighter gray, the birds chose the new brighter gray. Köhler concluded that his subjects had learned to choose the brighter stimulus, and then transposed this relational form to the test trials. Other studies with different species and stimulus dimensions yielded similar results (e.g., Anderson, Awazu, & Fujita, 2004; Manabe, Murata, Kawashima, Asahina, & Okutsu, 2009; Pepperberg & Brezinsky, 1991; Riley, Goggin, & Wright, 1963; Saldanha

& Bitterman, 1951; Schusterman & Krieger, 1986; Wiegmann, Wiegmann, MacNeal, & Gafford, 2000; Wright, Cook, & Kendrick, 1989; for a review, see Lazareva, 2012).

Spence (1936, 1937) questioned Köhler's interpretations. He reasoned that if, during the initial training, an excitatory gradient formed around the positive stimulus, *S*+, and an inhibitory gradient formed around the negative stimulus, *S*−, the sum of the two gradients could yield a net gradient with an excitatory peak at the new brighter gray. This peak could explain the preference for the new stimulus. According to Spence, we may not need to invoke relational processes if the interaction of simple excitatory and inhibitory generalization gradients predicts transposition (see also Mackintosh, 1974).

However, additional studies showed that the interaction of generalization gradients could not explain all instances of relational responding (e.g., the “intermediate size problem”; see Reese, 1968; Riley, 1968). It seems that both absolute and relational forms of responding may take place, although it is still unclear which variables determine whether one or the other (or both) occur (see Mackintosh, 1974).

In the present study, we extend the absolute/relational issue to the stimulus dimension of duration. Specifically, we ask whether temporal control in the temporal bisection task, one of the most widely used tasks to study timing, is absolute or relational. To answer the question, we follow Church and Deluty's (1977) rationale: Suppose subjects learn two matching-to-sample tasks sequentially. In Task A, they learn to choose a left comparison stimulus following a 1-s sample, and a right comparison stimulus following a 4-s sample. Successful performance in this task is consistent with two hypotheses. The absolute hypothesis states that the subjects learned to respond “left” after the 1-s sample and “right” after the 4-s sample (1s→left, 4s→right). The relative hypothesis states that the subjects learned to respond “left” after

Marília Pinheiro de Carvalho and Armando Machado, School of Psychology, University of Minho; François Tonneau, Núcleo de Teoria e Pesquisa do Comportamento, Federal University of Pará.

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Correspondence concerning this article should be addressed to Marília Pinheiro de Carvalho, School of Psychology, Animal Learning and Behavior Lab, Campus of Gualtar, 4710-057 Braga, Portugal. E-mail: marilia.pinheiro.carvalho@gmail.com

the short sample and “right” after the long sample (short→left, long→right).

To contrast the hypotheses, the experimenter then divides the subjects into two groups and exposes them to Task B. The absolute group learns the new mapping, 4s→right, 16s→left; the relative group learns the opposite mapping, 4s→left, 16s→right. Samples and comparisons are the same, but the mapping differs, and the question is which group learns Task B faster. If the discriminations learned in Task A rest on the absolute sample durations, the absolute group will learn Task B faster because it can transpose the 4s→right (absolute) mapping from A to B, whereas the relative group cannot. However, if the discriminations rest on the relative sample durations, the relative group will learn Task B faster because it can transpose the relative mapping short→left, long→right from A to B, whereas the absolute group cannot.

The results have been mixed: Two studies (Church & Deluty, 1977; Hulse & Kline, 1993) reported evidence more consistent with relational responding, and one study (Carvalho & Machado, 2012) reported evidence more consistent with absolute responding. Other studies with the bisection task, but using a different rationale, also reported mixed results, both with animals and humans (Maia & Machado, 2009; Molet & Zentall, 2008; Spínola, Machado, de Carvalho, & Tonneau, 2013; Zentall, Weaver, & Clement, 2004).

The reasons for these differences are unclear. The animal species, the sample modality, the amount of training, and the methods of data analyses have varied across studies. Perhaps even more important than these differences may be the fact that hypotheses limited to ordinal statements about speed of acquisition may be too broad and vague to test empirically. In Church and Deluty's (1977) study, for example, the relative group learned the 4-s discrimination in Task B faster than the absolute group, but the absolute group showed slightly better performance during the first session. Moreover, Church and Deluty did not report how fast the two groups learned the 16-s sample discrimination. Hence, the broad conclusion that the data supported the relational hypothesis is questionable.

Following Carvalho and Machado (2012), we propose an alternative, theoretically guided approach to the absolute/relational issue in the bisection task. In the spirit of Spence (1936, 1937), the approach adopts the simple null hypothesis that seemingly relational forms of responding in the bisection task are reducible to the effects of temporal generalization gradients. If Task A produces temporal generalization, and if responding to new stimuli depends, at least in part, on this generalization, then performance in Task B should be predictable from the generalization gradients induced by Task A. To test this hypothesis, we follow Church and Deluty's (1977) rationale but add generalization tests at the end of each bisection task to determine how well the temporal generalization gradients predict the performance of each group, following each sample, during the next bisection task.

Generalization gradients can predict performance only during the first trials of the new task, before the new contingencies take control of behavior. To predict the acquisition curves beyond the first trials, we need a theory or model that integrates timing and learning. The task is not easy, though, because most timing models deal exclusively with steady-state behavior.

Consider the most influential model, the scalar expectancy theory (SET; e.g., Gibbon, 1991; Gibbon, Church, & Meck, 1984). A

pacemaker emits pulses at rate λ , and an accumulator adds the pulses emitted during the to-be-timed interval, the sample in a temporal bisection task. When the sample ends and a response occurs and is reinforced, the number in the accumulator is multiplied by a random variable, k , and then stored in a memory indexed by the response. Thus, if left and right choices are reinforced after the short and long samples, respectively, the number in the accumulator is stored in the “left memory” when left is reinforced, and in the “right memory” when right is reinforced. Because λ and k are random variables, the values stored in each memory will vary across trials, and at the steady-state, each memory will contain a distribution of counts that represents the corresponding sample duration. To decide which key to choose on any given trial, the subject takes a sample from each of its two memories, X_{Left} and X_{Right} , and then compares them with the number in the accumulator, X_{Acc} . If the ratio $X_{\text{Acc}}/X_{\text{Left}}$ is less than the ratio $X_{\text{Right}}/X_{\text{Acc}}$, the subject chooses the left key; otherwise, it chooses the right key. This categorical decision rule predicts that the preference for the right key will be sigmoidal, increasing with sample duration from about 0 to about 1, and crossing the indifference point at the geometric mean of the trained samples.

Although SET predicts several properties of steady-state performance, it does not say anything about how the memory contents change with training, particularly when the animal learns a new task. For example, if the left key is correct after a 1-s sample in Task A, but after a 4-s sample in Task B, SET does not specify how the contents of the “left memory” change during Task B, that is, how the new 4-s sample counts replace the old 1-s sample counts. Without explicit statements about memory dynamics, the model cannot predict acquisition curves. Other timing models are similarly limited to steady-state behavior (e.g., the behavioral economic model of Jozefowicz, Staddon, & Cerutti, 2009; the drift diffusion model of Ratcliff & McKoon, 2008).

One model that predicts both acquisition curves and steady-state behavior is the learning-to-time (LeT) model (Machado, 1997; Machado, Malheiro, & Erlhagen, 2009). An outgrowth of Killeen and Fetterman's (1988) behavioral theory of timing, LeT integrates reinforcement, extinction, and temporal generalization processes to predict behavior across tasks. For these reasons, we use LeT to predict the pattern of acquisition curves and the shape of generalization gradients throughout the experiment.

The present study also improved the design followed in previous studies. First, in all of these studies, the comparison stimuli were left and right levers or keys. Because location distinguished the alternatives, motor patterns during the sample may have mediated the temporal discriminations (see Carvalho & Machado, 2012). To eliminate the potential confounds introduced by these patterns, we replaced the left–right comparisons with red–green comparisons, with their location randomized across trials.

Second, slowing acquisition may reveal more clearly the learning patterns of each group. To that end, we replaced the 1:4 ratio of sample durations used in previous studies (e.g., Carvalho & Machado, 2012; Church & Deluty, 1977) with a 1:3 ratio. Because temporal discrimination follows Weber's law, a

smaller ratio should reduce the discriminability of the sample durations and slow the approach to asymptotic performance.

Third, to have more opportunities to examine acquisition, we used an ABAB design. Phases A and B differed in the pair of training samples, 2 s versus 6 s in one, and 6 s versus 18 s in the other. The successive tasks preserved either the absolute or the relative mapping between samples and comparisons. Then, for each task and mapping, we (a) examined whether the generalization gradient obtained at the end of one task predicted performance during the first session of the next task, and (b) compared LeT's predictions against the pigeons' acquisition curves and generalization gradients.

The LeT Model

We describe the model's architecture and then explain qualitatively how it works in two successive bisection tasks (for equations, see [Carvalho & Machado, 2012](#); [Machado et al., 2009](#)). LeT has three components (see [Figure 1](#), first row), a series of *behavioral states* connected by *associative links* to the two *operant responses*. The onset of the sample activates the first state. After a while, that state becomes inactive and the second state becomes active. After another period of time, the second state becomes inactive and third becomes active, and the process repeats, with the activation passing to the next state in the series. The speed of activation of successive states is a Gaussian random variable, λ , with mean μ_λ and standard deviation σ_λ ; λ is sampled at trial onset.

At the end of the sample, one state will be active and the strengths of its two links—quantities between 0 and 1—determine the choice probabilities. If the link with one response, say, *red*, is stronger than the link with the other response, *green*—in other words, if the links from the active state are biased toward red—the probability of choosing red will be greater than the probability of choosing green.

After the choice response, reinforcement or extinction follows. Each of these outcomes changes the links from the active state to the emitted (W_E) and nonemitted (W_{NE}) response. Reinforcement strengthens W_E by the amount $\beta(1-W_E)$, and weakens W_{NE} by the amount βW_{NE} , where $\beta > 0$ is a reinforcement parameter; extinction weakens W_E by the amount αW_E , and strengthens W_{NE} by the amount $\alpha(1-W_{NE})$, where $\alpha > 0$ is an extinction parameter.

To summarize, the sample duration determines probabilistically the state that is active at the end of the sample, and the reinforcement contingencies, through their biasing effect upon the associative links, determine the choice probabilities. The model uses five parameters, μ_λ and σ_λ , related to state activation, α and β , related to learning, and W_0 , the link strength of all states before the experiment. For steady-state predictions, only two parameters are critical, the ratios $\sigma_\lambda/\mu_\lambda$ (the “clock's” coefficient of variation) and α/β (the relative effects of extinction and reinforcement).

To understand the model's predictions, [Figure 1](#) illustrates its typical output at the end of Phase A (second row) and during a Phase B that preserves either the relative (third row) or the absolute (fourth row) mapping. The left panels single out the three states most likely to be active at the offset of the 2-, 6-, and 18-s samples. We refer to them as Modal States 2, 6, and 18, respec-

tively, and to their links with “Red” and “Green,” as, for example, 2→Red or 6→Green. The model predictions do not depend on the specific number of the modal states.

During Phase A, reinforcement strengthens the links 2→Red and 6→Green, and extinction weakens the links 2→Green and 6→Red; the links from State 18 remain unchanged because State 18 is rarely active after 2- or 6-s samples. At the end of training, the links from States 2 and 6 sustain accurate performance following each sample, a result shown in the second row of [Figure 1](#) for the last two sessions. The right panel shows the generalization gradient at the end of Phase A. The probability of choosing green, $P(\text{“Green”})$, is close to 0 when the sample is 2 s or less, increases to approximately 1 as the sample ranges from 2 s to 6 s, and then decreases to chance after the longest samples. The return to chance occurs because the states active after the longest samples were not active during training and therefore preserved their initial, unbiased links with the two responses. The gradient predicts the pattern of choices during the first session of Phase B.

The third row corresponds to a Phase B that preserves the relative mapping. The contingencies 6s→Red, 18s→Green change the links from State 6, reversing their bias from green to red, and the links from State 18, biasing them to green. The links from State 2 retain their bias for red because, even though State 2 is seldom active during Phase B, on the few trials it is active, the sample is most likely 6-s long and red remains the reinforced choice. The middle panel shows the acquisition curves. The percentage of correct responses after the 6-s sample starts below chance (as predicted by the gradient of Phase A) and increases with training, whereas the percentage of correct responses after the 18-s sample starts at chance (also as predicted by the gradient from Phase A) and increases with training. The right panel shows the gradient at the end of Phase B. With respect to Phase A, the gradient simply shifts to the right.

The fourth row shows a transition that preserves the absolute mapping. Because the link 6→Green is preserved, the percentage of correct choices after the 6-s sample starts close to 100 (as the generalization gradient from Phase A predicted) and remains high, whereas the corresponding figure for the 18-s sample starts close to chance (also predicted by the gradient from Phase A) and increases subsequently. At the end of Phase B, modal States 2 and 18 are biased toward red, and therefore the generalization gradient adopts an inverted V shape, with $P(\text{“Green”})$ close to 1 at 6 s, and decreasing to 0 both at 2 s (the retained effect of Phase A) and 18 s (the effect of Phase B). However, $P(\text{“Green”})$ at 2 s is not as low as at the end of Phase A, because on the few trials State 2 was active, the contingencies of Phase B biased choice toward green, thereby undoing some of the effects of Phase A.

As we show in the Results section, LeT predicts distinct acquisition curves and generalization gradients for each phase and mapping of the experiment. We take these curves and gradients, obtained with the same set of parameters, as our null hypothesis. By contrasting them against the pigeon data, we expect to achieve two goals—to clarify the absolute/relational issue in the bisection task, and to determine how much data a model based on stimulus generalization, reinforcement, and extinction—a Spencean model—can explain.

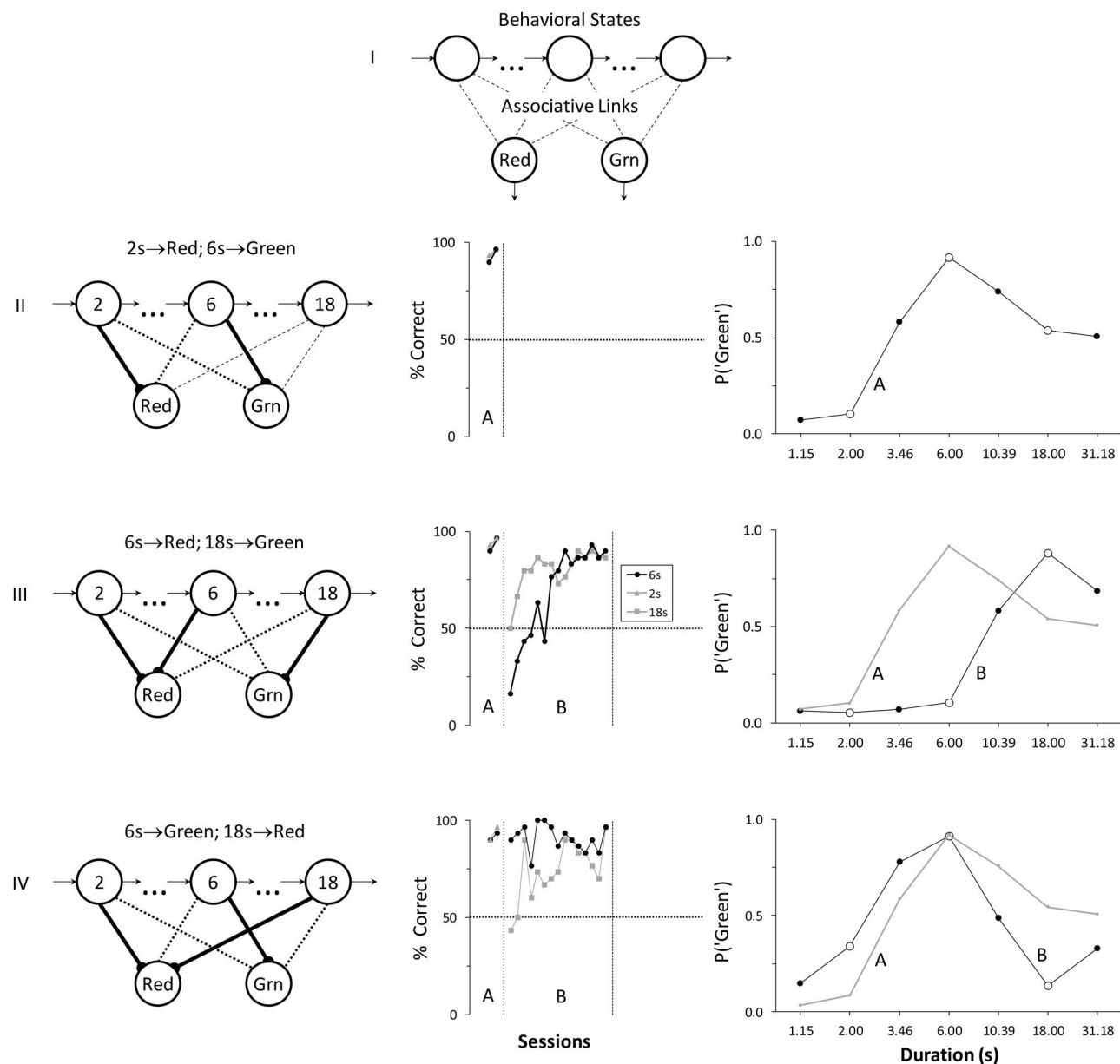


Figure 1. Row I: Structure of the learning-to-time model. A set of behavioral states, activated serially, control the operant responses through vectors of associative links whose strengths change with reinforcement and extinction. Row II: Model predictions for the task 2s→Red, 6s→Green (Phase A). The left panel shows the link strengths of the modal states, the middle panel shows the acquisition curves, and the right panel shows the generalization gradients. Row III: Model predictions for Phase B, 6s→Red, 18s→Green (relative group). Row IV: Model predictions for Phase B, 6s→Green, 18s→Red (absolute group).

Method

Subjects

Four naïve pigeons (P229, P230, P273, and P451) and four pigeons with experience in a number discrimination procedure (P154, P389, P751, P762) participated in the experiment. Their mean age at the time of the experiment was 6.75 years (range = 3–10). They were maintained at 85% to 90% of their free-feeding

weight, with grit and water continuously available in their individual home cages. The colony room was under a 13:11-hr light–dark cycle, with lights on at 8:00 a.m.

Apparatus

We used four standard operant chambers for pigeons from Med Associates. In the back panel of each chamber, a 7.5-W houselight provided general illumination. In the front panel, a 6

cm high \times 5 cm wide feeder opening, centered horizontally and 3.5 cm above the floor grid, provided access to mixed grain. The feeder was illuminated with a 7.5-W light. The front panel also contained three 2.5-cm-diameter keys, arranged in a row, 18.5 cm above the grid floor, and 9 cm apart, center to center. The center key could be illuminated with a white hue and the side keys could be illuminated with red and green hues. Each chamber was enclosed in a wooden box, itself equipped with a fan that circulated air and helped mask extraneous noises. A personal computer programmed with Visual Basic 2008 and using the Whisker software (Cardinal & Aitken, 2010) controlled the experimental events and recorded the data.

Procedure

General design. The pigeons learned two bisection tasks, one using 2-s and 6-s samples, and another using 6-s and 18-s samples. Half of the subjects learned the 2 s versus 6 s task first and the 6 s versus 18 s task next (*upshift* subjects), and the other half learned the tasks in the opposite order (*downshift* subjects).

The experiment followed an ABAB design. We refer to the four phases as A, B, A', and B'. For the upshift subjects, A and A' refer to the 2 s versus 6 s task, and B and B' refer to the 6 s versus 18 s task; for the downshift subjects, A and A' refer to the 6 s versus 18 s task, and B and B' refer to the 2 s versus 6 s task.

Following Church and Deluty's (1977) design, we further divided the four upshift and the four downshift subjects into two groups, relative and absolute, yielding four groups of two pigeons each (see Table 1).

Throughout the study, the comparison stimuli were the red and green keylight colors. Which comparison was correct following a given sample was counterbalanced across subjects, but, for clarity, we describe the task as if only the mappings shown in Table 1 were used.

Training. A training trial began with a 30-s intertrial interval (ITI) during which all lights were off. After the ITI, the houselight and the center keylight turned on for the duration of the sample. When the houselight and the center keylight turned off, the two side keys turned on, one with red and the other with green light (location counterbalanced across trials). A peck to one of the side keys turned both of them off. If the peck was at the correct comparison, the feeder was activated for 3 s and then the ITI started; if the peck was at the incorrect comparison, the ITI started immediately.

Each session comprised 60 trials, 30 for each sample, presented in random order but with the constraint that no more than four trials of the same sample occurred consecutively. Training continued for a minimum of 15 (Phases A and B') or 20 (Phases B and

A') sessions and until the subject achieved at least 80% of correct responses following each sample. A correction procedure was in effect only during Phase A. Under the correction procedure, an incorrect choice repeated the trial three times at most. If the incorrect response persisted, the fourth trial presented only the correct comparison. The correction trials were not included in data analysis.

Generalization test. After the pigeons met the learning criterion, we conducted a single test session with 100 trials, 60 regular trials (30 for each training sample), and 40 test trials. The test trials were equal to the training trials in all details except two: The sample duration differed from the training durations, and choices were not reinforced. The test trials included five different sample durations, each presented on eight trials. The training and test durations equaled (note log spacing) 1.15 s, 2.00 s, 3.46 s, 6.00 s, 10.39 s, 18.00 s, and 31.18 s. The 3.46-s and 10.39-s durations correspond to the geometric means of the training samples. The first 10 trials of the test session were always regular training trials, five with each trained duration. After the generalization test session, training resumed for two sessions to reduce potential effects of test and ensure accurate performance to both trained samples before changing phase.

Transition between phases. The first session of a new phase (B, A', and B') began with 10 training trials of the previous phase, five with each trained duration, and continued with 60 training trials of the new phase. (Data analyses for the first session of each phase excluded the first 10 trials.) From the second session onward, training proceeded as described in the Training section.

Model Simulation

To compare LeT with the pigeons' behavior, we conducted two computer simulations for each of the four groups (mimicking the eight subjects in the study), across the ABA'B' phases, with 15 sessions per phase, and the same number of trials per session as the pigeons. Moreover, to isolate the model's response to the reinforcement contingencies of each group and phase, we used the same parameter values for all simulations. They were $\mu_\lambda = 1.0$, $\sigma_\lambda = 0.3$, $\alpha = .05$, $\beta = .04$, and $W_0 = 0.1$. These values are similar to those used in previous studies (e.g., Carvalho & Machado, 2012), but the model is robust to parameter changes. For each training session, we obtained the percentage of correct responses following each sample, and for each test session, we obtained the proportion of responses to green following each sample. Acquisition curves and generalization gradients defined the model's predicted output for each phase.

Table 1
Experimental Groups and the Bisection Tasks to Which They Were Exposed Across Phases

Phase	Upshift		Downshift	
	Relative	Absolute	Relative	Absolute
A	2s→Red, 6s→Green	2s→Red, 6s→Green	6s→Green, 18s→Red	6s→Green, 18s→Red
B	6s→Red, 18s→Green	6s→Green, 18s→Red	2s→Green, 6s→Red	2s→Red, 6s→Green
A'	2s→Red, 6s→Green	2s→Red, 6s→Green	6s→Green, 18s→Red	6s→Green, 18s→Red
B'	6s→Red, 18s→Green	6s→Green, 18s→Red	2s→Green, 6s→Red	2s→Red, 6s→Green

Results

All pigeons mastered the two discriminations of each phase, taking, on average, 26.4 sessions in Phase A, 23 in Phase B, 20 in Phase A', and 15 in Phase B'. To compare the acquisition rates in each phase, we examined the number of sessions required to meet the 80% criterion on the 6-s common sample and on both samples. With respect to the 6-s sample, two-tailed *t* tests revealed that the absolute group needed fewer sessions than the relative group in Phases B ($\bar{x} = 2.0$ vs. $\bar{x} = 6.5$, $t[6] = 3.25$, $p = .017$, Cohen's $d = 2.3$, 95% confidence interval [CI] [0.37, 4.13]) and B' ($\bar{x} = 1.25$ vs. $\bar{x} = 4.5$, $t[6] = 3.28$, $p = .017$, Cohen's $d = 2.31$, 95% CI [0.38, 4.16]). The upshift and downshift groups did not differ in Phases B, A', and B' (all $ps > .05$). With respect to both samples, the relative and the absolute groups differed only in Phase B, with the relative group meeting the criterion in fewer sessions than the absolute group ($\bar{x} = 7.75$ vs. $\bar{x} = 16.0$, $t[6] = 4.01$, $p = .007$, $d = 2.84$, 95% CI [0.70, 4.88]). The upshift and downshift groups did not differ in any phase ($ps > .05$).

In summary, the absolute group acquired the correct response to the 6-s sample faster than the relative group, a result at odds with

Church and Deluty (1977) and Hulse and Kline (1993). However, the relative group acquired the correct responses to both samples faster than the absolute group. This last result stemmed, at least in part, from trade-offs in the acquisition of the correct responses. For some subjects, particularly in the absolute groups, although the correct response to one sample increased, the correct response to the other sample decreased, until both responses met the learning criterion. We show acquisition curves with these trade-offs when presenting individual data for both the relative and absolute groups, and we elaborate on this finding in the Discussion section.

Relative Groups

Relative upshift. Figure 2 shows the individual data (top two rows) and the model's predictions (bottom row). The percentage of correct responses after the 6-s sample decreased after each phase transition and then increased with training. This result is consistent with LeT (cf. bottom row). With respect to the other training samples, in Phase B, performance after the 18-s sample started somewhat above chance for Pigeon P762, as LeT predicts, but close to 100 for Pigeon P154, a result inconsistent with LeT. In

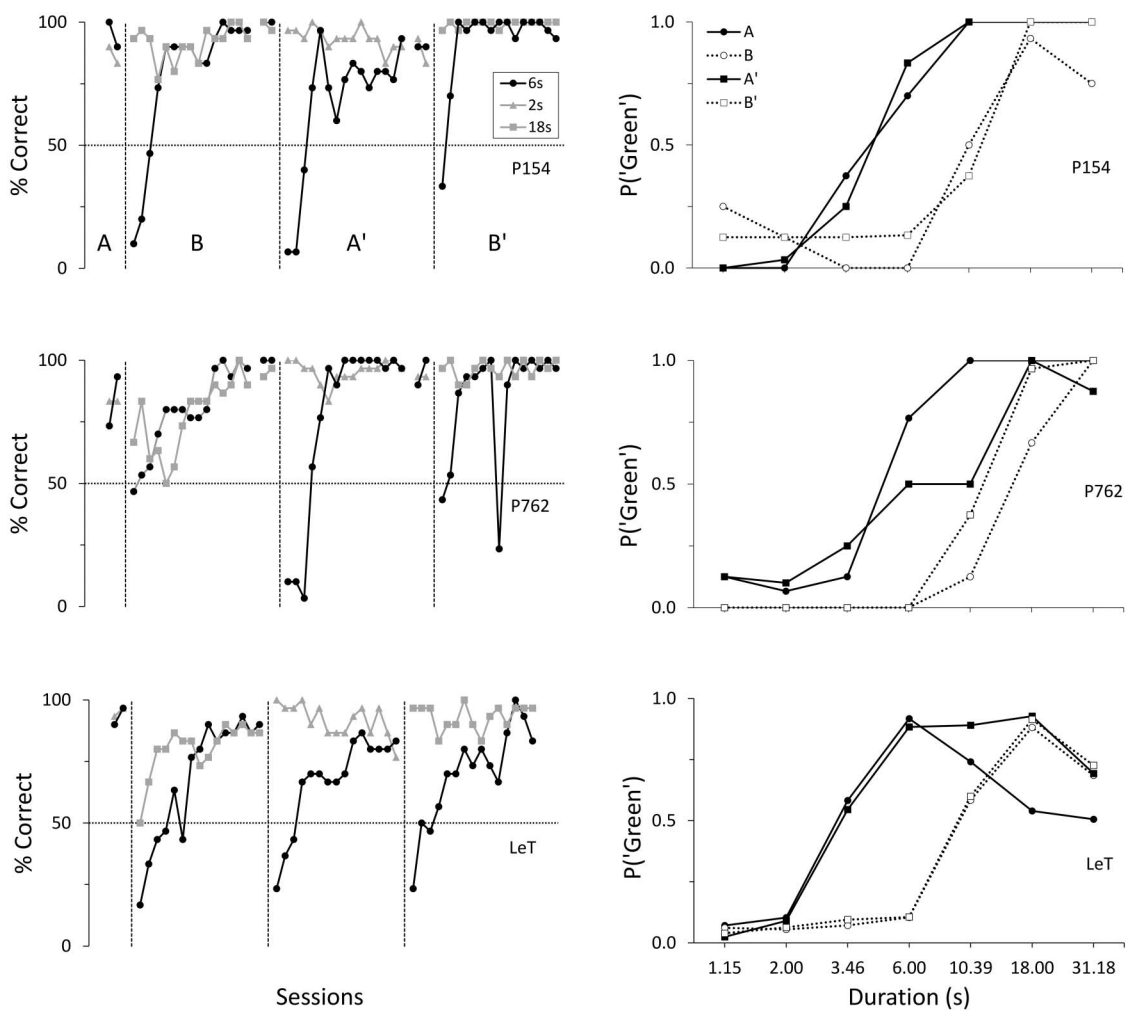


Figure 2. Acquisition curves (left) and generalization gradients (right) for the two pigeons of the relative-upshift group (top and middle rows) and corresponding model predictions (bottom row).

subsequent phases, performance following the 2-s (A') and 18-s (B') samples remained always close to 100, a result also consistent with LeT.

The generalization gradients for each pigeon were roughly ogival. In Phase A, P("Green") was close to 0 for 2-s and shorter samples, increased as the sample ranged from 2 to 6 s, and then reached 1 for longer samples. In Phase B, the ogives shifted to the right so that P("Green") remained close to 0 up to 6 s, and then increased to 1 at 18-s or longer samples. The gradients of Phases A' and B' were roughly similar to the gradients of Phases A and B, respectively.

With two exceptions, the pigeon gradients were consistent with LeT. The first exception was the value of P("Green") at the longest samples, particularly in Phase A. Whereas the pigeons' gradients remained close to 1, LeT's gradients decreased to chance. The second exception was the peak-shift-like effect observed in Phases A and A' when the longest samples occasioned more Green responses than the 6-s sample. LeT does not predict this effect.

To measure the match between model and data, we fitted the model to the four data sets of each pigeon simultaneously (i.e., 28

data points) and then computed the variance accounted for, ω^2 . It equaled .75 for P154, and .63 for P762.

Relative downshift. The acquisition curves (Figure 3, top rows) show that correct performance decreased severely after the 6-s sample, but remained accurate after the other samples. Both patterns are consistent with LeT (cf. bottom panel). In Phase B', Pigeon P451 showed the aforementioned trade-offs, because performance at the 2-s sample decreased as performance at the 6-s sample increased.

With respect to the generalization gradients, in Phase A, the gradient decreased for durations within the trained range of 6 s and 18 s. The gradient then shifted to the left in Phase B, returned to the right in Phase A' (but this time retaining the high value at the shortest samples), and finally shifted to the left again in Phase B'. The generalization gradients were also broadly consistent with LeT (for P230, $\omega^2 = .81$; for P451, $\omega^2 = .80$). But there were inconsistencies between model and data in Phase A, because durations shorter than 6 s occasioned at least as many Green responses as the 6-s sample, whereas LeT predicts a return to indifference, and in Phases B and B', because durations longer

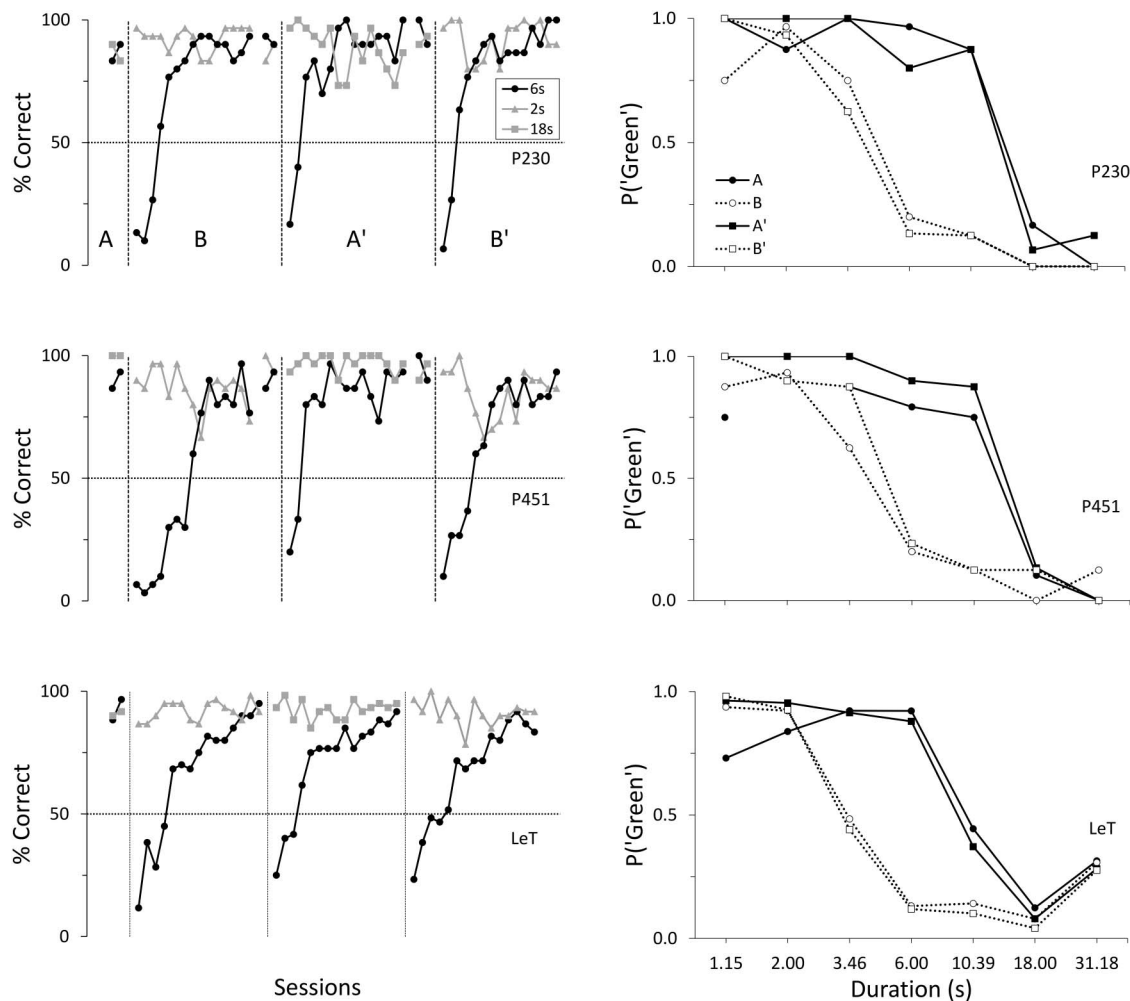


Figure 3. Acquisition curves (left) and generalization gradients (right) for the two pigeons of the relative-downshift group (top and middle rows) and corresponding model predictions (bottom row). Because of a programming error, the 2-s sample was not presented in the generalization test session of Phase A for P451.

than 6 s occasioned more Red responses than the 6-s sample (the peak-shift-like effect).

Absolute Groups

Absolute upshift. Figure 4 shows that at the beginning of each phase, the pigeons' performance after the 6-s sample was always significantly above chance, a result consistent with LeT. Their performance after the 18-s sample in Phase B and the 2-s sample in Phase A' was less accurate than after the 6-s sample, a result also consistent with LeT. However, LeT did not predict performance significantly below chance, as both pigeons showed in Phase B and Pigeon P751 showed in Phase A'. In Phase B', performance of Pigeon P751 on the 18-s sample was accurate since the first sessions, as LeT predicted, but that of Pigeon P229 started at chance, a result LeT did not predict. Acquisition trade-offs occurred in Phases B and A' for Pigeon P229.

The generalization gradients in Phase A were ogival and approached 1 at samples longer than 6 s. At the end of the remaining phases, the gradients approached the inverted V shape that LeT

predicted with the mode at or close to 6 s. Except for the high value of $P(\text{"Green"})$ at the two longest samples in Phase A, the generalization gradients were broadly consistent with LeT (for P229, $\omega^2 = .63$; for P751, $\omega^2 = .71$).

The low percentages of correct responses after the 18-s (Phase B) and the 2-s samples (Phase A'), although inconsistent with LeT, were consistent with the generalization gradients obtained in the preceding phases. In Phase A, the two individual gradients showed a high value of $P(\text{"Green"})$ at the 18-s duration, which predicts the close-to-zero percentage of correct responses (Red) observed at the beginning of Phase B. Similarly, in Phase B, the gradient of P229 showed a high value of $P(\text{"Green"})$ at the 2-s duration, which predicts the below chance percentage of correct responses (Red) observed at the beginning of Phase A'.

Absolute downshift. In Phases B and B' (Figure 5, top rows), performance started high, as LeT predicted, but then, in Phase B, it followed a U-shaped curve that was particularly pronounced in Pigeon P389, another instance of trade-offs. In the first sessions of Phase A', Pigeon P273 showed a percentage of correct responses

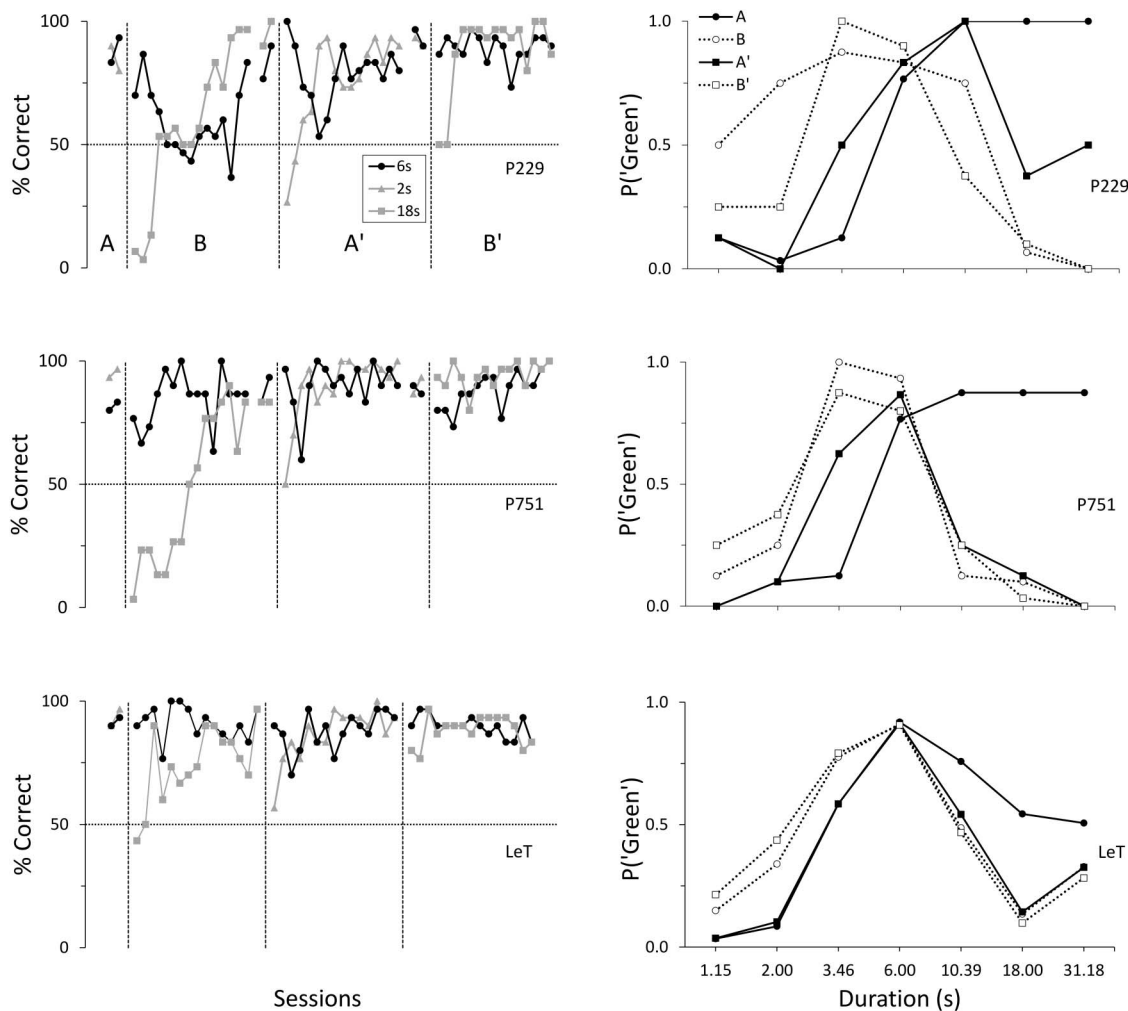


Figure 4. Acquisition curves (left) and generalization gradients (right) for the two pigeons of the absolute-upshift group (top and middle rows) and corresponding model predictions (bottom row).

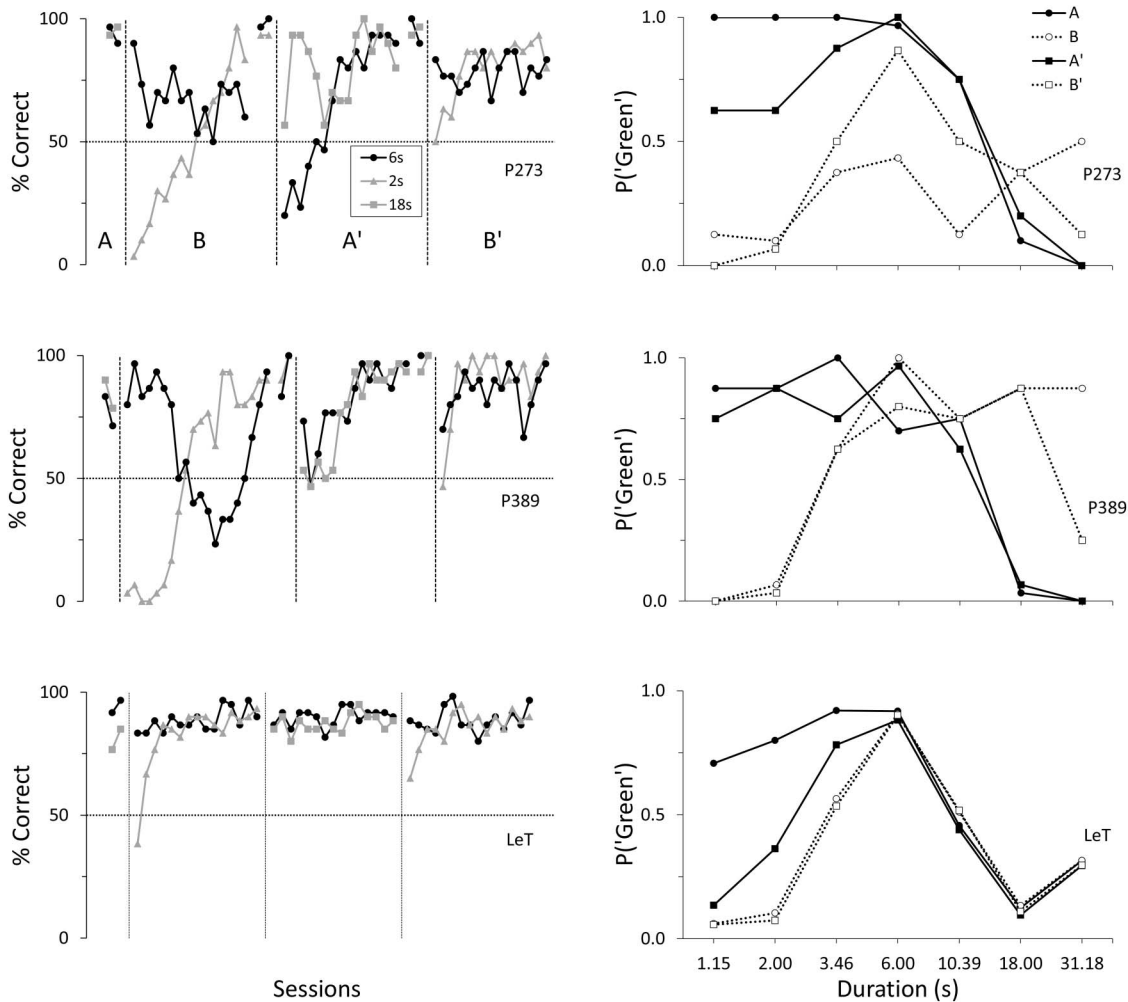


Figure 5. Acquisition curves (left) and generalization gradients (right) for the two pigeons of the absolute-downshift group (top and middle rows) and corresponding model predictions (bottom row).

significantly below chance. This result was the most inconsistent with LeT. Correct responses after the 2-s sample began markedly below chance in Phase B, and close to chance in Phase B'. Correct responses after the 18-s sample started at chance in Phase A', and then increased smoothly for Pigeon P389, and erratically for Pigeon P273.

At the end of Phase A, the two gradients were descending ogives, as LeT predicted, but with higher left limbs. In Phase B, Pigeon P273 showed marked bias for the red key, and both pigeons showed relatively high values at 18-s and longer samples. In the last two phases, the gradients differed between the two pigeons. For P273, the gradients in Phases A' and B' were roughly inverted-V-shaped as LeT predicted. For P389, the gradients were a descending (A') and an ascending (B') ogive, the latter with a low value at the longest duration. Consistently, ω^2 was smaller for the absolute downshift (.57 for P273; .35 for P389).

Aggregate Data

The LeT model predicted three main results concerning the acquisition curves. First, at each phase transition, performance

following the 6-s common sample should be below chance in the relative groups but above chance in the absolute groups. In the top row of Figure 6, the symbols show the percentage of correct responses following the 6-s sample during the first session of Phases B, A', and B' predicted by the model (left panel) and obtained with the pigeons (right panel). With one exception, the pattern of results is consistent with the model.

Second, there should be some generalization from the 6-s sample to the 2-s sample. Therefore, training with the 6-s and 18-s samples in one phase should affect the choices the pigeons learned to make after 2-s sample in the preceding phase. However, the effect should be positive for the relative groups, and negative for the absolute groups. In addition, the positive effects should be small because of a ceiling in choice proportion, whereas the negative effects should be large.

The middle panels of Figure 6 show percent correct after the 2-s sample during two sessions, the last session of the first phase with that sample (filled circles) and the first session of the second phase with that sample (empty circles). The difference between the two data points reveals the effect of the training phase that occurred

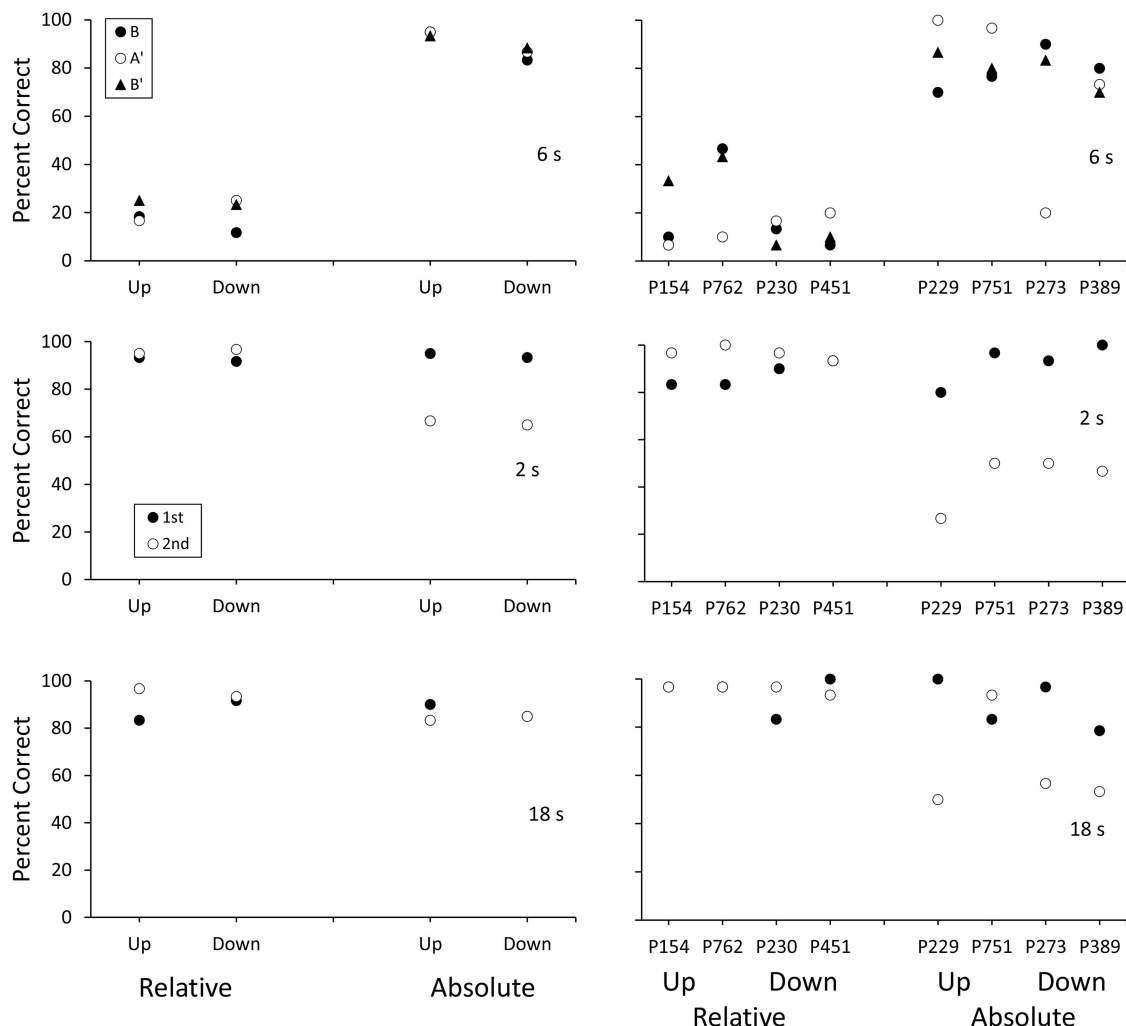


Figure 6. The symbols show the percentage of correct responses following the 6-s, 2-s, and 18-s samples in the first session of Phases B, A', and B', as predicted by the model (left) and as observed in the pigeons' performance (right).

between the two sessions. The relative groups showed small positive differences, whereas the absolute groups showed large negative differences.

Third, according to LeT, there should be less generalization from the 6-s sample to the 18-s sample. Therefore, training with 2-s and 6-s samples in one phase should not affect the choices learned in a previous phase with the 18-s sample. The bottom panel of Figure 6 shows that all four pigeons from the relative groups, and one pigeon (P751) from the absolute groups, corroborated the prediction, but the other pigeons showed a significant loss in performance.

Concerning the generalization gradients, LeT predicted two main results. First, the gradients obtained at the end of one phase should predict choice during the beginning of the next phase. Figure 7 plots the choice proportions obtained during the first session of a new phase against the proportion predicted by the generalization gradient from the previous phase. For seven of the eight pigeons (except P389), a linear function described the data

well; the correlations averaged .96 (range = .91–.99) and the slopes averaged 0.95 (range = .71–1.14). The same analysis, but using only the first half of the session of the new phase, yielded similar results, an average correlation of .96 and slope of 1.0.

Second, the gradients for the relative and absolute groups should differ markedly in shape. To check this prediction, we averaged the gradients from the upshift and downshift groups after rotating the gradients from the downshift groups 180° around the 6-s vertical line. The rotation aligned the trends of the two gradients and made their averaging meaningful. The symbols in Figure 8 show the results.

In addition, we asked whether LeT could fit *simultaneously* the four generalization gradients of each pigeon by (a) varying only its two critical parameters, the ratios $\sigma_\lambda/\mu_\lambda$ and α/β ; and (b) using only the two points of each gradient corresponding to the training samples of each phase. Each of these two points represented 30 trials, whereas the data from any other sample represented eight trials. The lines in Figure 8 show the results.

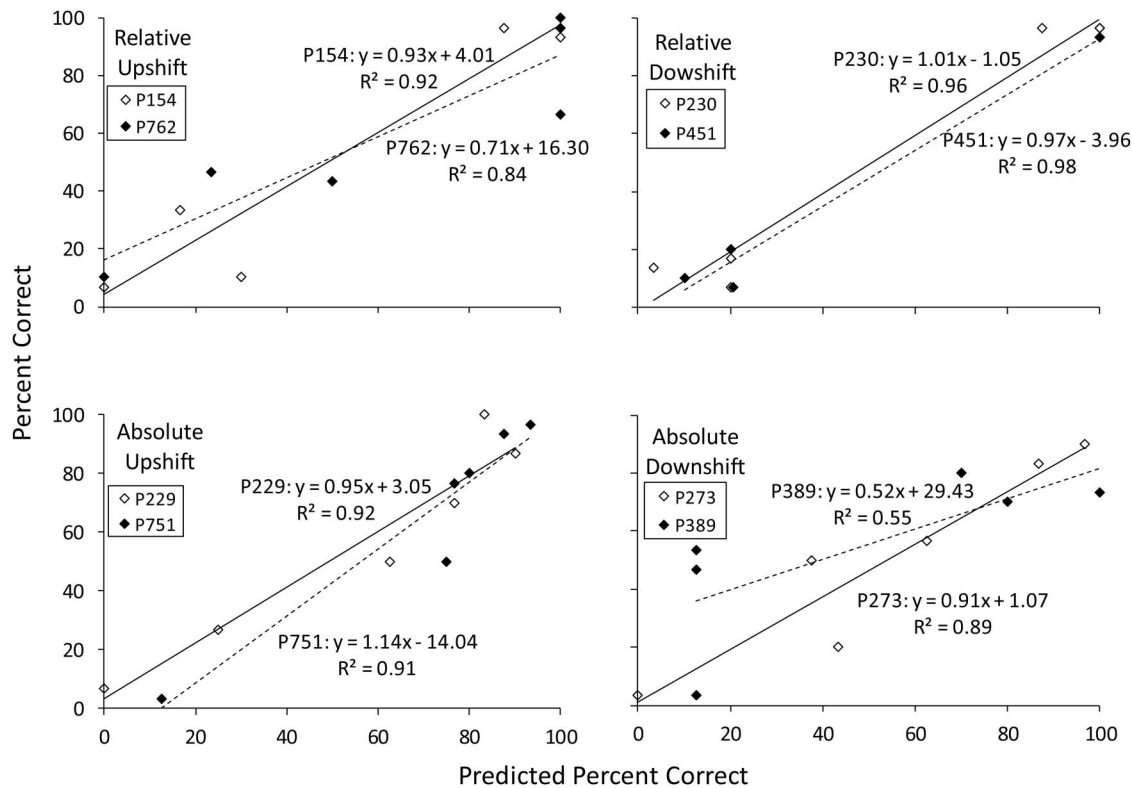


Figure 7. The symbols show the percentage of correct responses observed during the first session of Phases B, A', and B', plotted against the values predicted from the generalization gradient of the previous phase. The lines are the best-fitting regression lines.

The average gradients of the relative groups (top row) were shifted ogives, increasing from about 0 to about 1 and with bisection points close to the geometric mean of the trained samples. LeT fit the gradients well except at the longest samples in Phase A ($\omega^2 = .79$ in A; .99 in B; .93 in A'; .96 in B'). For the absolute groups (bottom row), the average gradients changed across phases from an ogive to an inverted V-shaped curve with a mode at 6 s. The main local discrepancy between model and data occurred again at the right tail of the gradient from Phase A. The ω^2 values equaled .83, .59, .69, and .74 in Phases A, B, A', and B', respectively. For both data and model, the bisection points were close to the geometric mean of the trained samples.

Discussion

In the present study, we extended Spence's (1936, 1937) approach to the time domain, that is, we attempted to explain seeming forms of relational responding in the bisection task by means of temporal generalization and the combination of temporal generalization gradients. We proceeded through a series of increasingly more demanding tests. In the first test, we used the generalization gradient obtained at the end of one phase to predict choice at the beginning of the next phase. In this case, we did not need a theoretical model to predict that the values of P("Green") at the end of one phase should be close to the values of P("Green") during the first session of a new phase. The data confirmed the prediction. For most pigeons and phases, the correlations between

the two sets of values were positive and strong, and the least-squares regression lines had slopes close to 1.

In two other tests, we attempted to predict the pattern of the acquisition curves after each phase transition and the shape of the generalization gradients at the end of each phase. In these cases, we needed a theoretical model to specify how the tendencies to choose the comparisons following the trained samples change with the reinforcement contingencies of each phase, and how they generalize to other samples. The LeT model served this purpose. It operationalized the Spencean approach—with its processes of temporal generalization (state dynamics), reward following (learning rules), and temporal memory (associative links from the states to the responses)—and predicted the pattern of acquisition curves and the shape of the generalization gradients. We proposed it as a null hypothesis.

In what follows, we assess how well LeT fared as a null hypothesis, and then address the implications of its fits and misfits of the data to our understanding of the absolute/relational issue in the temporal bisection task.

Generalization Gradients

For Phase A, LeT predicted a gradient that, within the range of the two training samples, increased monotonically from about 0 to about 1, and that, outside the range, approached .5. For the remaining phases, LeT predicted shifted ogives for the relative groups and inverted V-shaped curves for the absolute groups. The

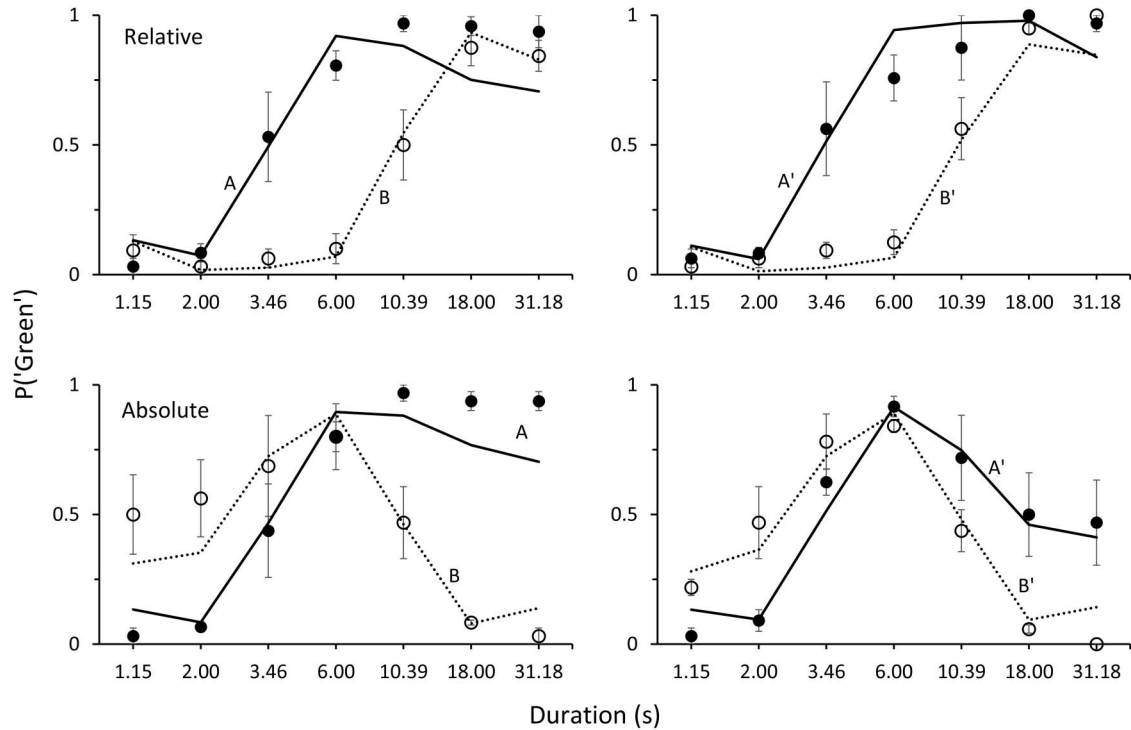


Figure 8. The symbols show the average (\pm SEM) generalization gradients for the relative (top) and absolute (bottom) groups. The lines are the average of the individual gradients fit by the learning-to-time model. The data from the downshift pigeons were reflected around the 6-s vertical line before averaging them with the data from the upshift subjects. The left panels show data from Phases A and B, and the right panels show data from Phases A' and B'.

data were broadly consistent with these predictions (see Figures 2–5 and 8).

But there were two systematic deviations. First, in Phase A, obtained and predicted gradients differed at sample durations outside the training range. LeT predicted a return to indifference, but the pigeons showed a sustained preference for the “short” key after the shortest test samples and for the “long” key after the longest test samples.

Second, given any reasonable value for the Weber fraction (in LeT, the ratio $\sigma_\lambda/\mu_\lambda$), the generalization gradient induced by the 18-s sample should not overlap the gradient induced by the 2-s sample. In model terms, the set of states active after the 18-s sample and the set of states active after the 2-s sample should have few or no elements in common. Therefore, if the contingencies associated with the 6-s sample do not change across phases (absolute groups), the behavior occasioned by the 18-s sample in one phase should be retained during training with the 2-s sample in the next phase. Although some gradients strongly supported this prediction (e.g., the gradients for P751 in Figure 4 and the other inverted V-shaped gradients in Figures 4 and 5), others showed more changes than expected (the bottom panel of Figure 6 summarizes the discrepancies). These discrepancies contrast with the mostly correct predictions concerning the 2-s sample (see Figure 6, middle panel).

The discrepancies between model and data concerning the shape of the generalization gradients pose a difficult problem. On the one hand, monotonic generalization gradients with sustained low and

high tails outside the training range (as in Phase A) suggest simple categorical decision rules of the sort “Choose Red after samples below 3.5 s and Green after samples above 3.5 s.” Such rules occur in the leading timing model, SET. On the other hand, nonmonotonic gradients (e.g., inverted V-shaped gradients) rule out such categorical decision rules. To illustrate, if a pigeon learns the mapping 2s→Red, 6s→Green in Phase A, its strong tendency to choose red at the end of 2-s and shorter samples agrees with a categorical decision rule. If it then learns the mapping 6s→Green, 18s→Red in Phase B, a similar categorical rule entails a tendency to choose green at the end of 6-s and shorter samples, eliminating the tendency acquired in Phase A to choose red after 2-s and shorter samples.¹ Hence, any evidence that the pigeon preserved, albeit incompletely, the tendencies acquired during Phase A—evidence such as an inverted V-shaped gradient—would seem to reject simple categorical decision rules.

Other studies have found both gradient shapes. Using rats, Russell and Kirkpatrick (2007) and Siegel (1986) reported nonmonotonic gradients with tails that approached indifference outside the trained range, as LeT predicts. Using pigeons, Vieira de Castro, Machado, and Tomanari (2013) reported monotonic gradients with nondecreasing tails, gradients consistent with simple categorical decision rules but inconsistent with LeT. Future exper-

¹ For this reason, SET *always* predicts shifted ogives in the bisection task.

iments should investigate the reason for these differences across studies and discover when one or the other type of gradient obtains. Future analyses should also answer two theoretical questions: (a) How can we modify a model such as LeT to mimic categorical-like decision rules, and (b) How can we modify a model such as SET or other categorical-based models to account for the retention of learning across temporal tasks? The present findings suggest a partial answer. A categorical rule seems to apply when the animal first experiences sample durations outside the trained range (Phase A); a noncategorical rule seems to apply when the animal has previously experienced those sample durations (subsequent phases).

Acquisition Curves

According to LeT, at each phase transition, the relative groups should show more errors after the 6-s sample than after the 2-s or 18-s samples; the absolute groups should show the opposite pattern. Again, most results were consistent with the predicted trends, but a few were not. Some of the inconsistencies stem from the model incorrectly predicting the shape of the gradient outside the training range. If at the end of Phase A the model predicted indifference after the 18-s sample but the pigeons strongly preferred green, a fortiori the model also predicted incorrectly the acquisition curve for the 18-s sample at the beginning of Phase B. However, other inconsistencies were of a different sort. The absolute-downshift pigeons showed acquisition curves with more errors after the 6-s than the 18-s sample in Phase A'. These results were the most inconsistent with LeT (see [Carvalho & Machado, 2012](#), for a similar finding).

Although we do not know why the absolute-downshift pigeons made a large number of errors after the 6-s sample in Phase A', we note that during the preceding phase, they also showed acquisition curves with pronounced trade-offs (see [Figure 5](#)). These trade-offs also occurred in the relative groups (cf. [Figure 2](#), Pigeon P762 in Phase B; [Figure 3](#), Pigeon P451 in Phase B'), but they seemed to be more frequent or pronounced in the absolute groups (in addition to P273 and P389, see also [Figure 4](#), P229 in Phases B and A'). In [Carvalho and Machado's \(2012\)](#) study, it was also the case that the pigeons that showed the acquisition curves most at odds with LeT also showed "a negative covariation during the first sessions between proportion correct following 4-s sample and proportion correct following 16-s sample" (p. 37)—in other words, trade-offs.

Blocks of sessions during which the discriminative behavior after two or more samples covaries negatively have occurred in other studies. [Vyazovska, Teng, and Wasserman \(2014\)](#) reported negative covariations in a go/no-go task with 16 stimuli, defined by four binary dimensions (large/small, circle/square, bright/dark, and with a horizontal/vertical bar), with one stimulus positive (e.g., a large circle with a bright background and a horizontal bar) and the other 15 negative. Some pigeons showed severe upswings and downswings in response rate to the negative features, which occasioned large changes in the discrimination ratios across sessions. The authors described these findings as *attentional* trade-offs and related them to some pigeons' limited capacity to process multiple stimulus dimensions. The same authors did not find as large changes in discrimination ratios in a simultaneous discrimination task ([Teng, Vyazovska, & Wasserman, 2015](#)).

[Carvalho and Machado \(2012\)](#) advanced a more specific hypothesis to explain the trade-offs. The bisection task involves two conditional discriminative stimuli, the sample durations, and two simple discriminative stimuli, the keylight colors. The trade-offs could be related to competition between the two classes of stimuli triggered by extinction. Take the case of Pigeon P389 (see [Figure 5](#)). The pigeon learned the mapping 6s→Green, 18s→Red in Phase A, and then the mapping 2s→Red, 6s→Green in Phase B. In the first sessions of Phase B, the pigeon experienced massive extinction for choosing green after the 2-s sample. Such extinction episodes, and the occasional reinforcements for choosing red after the 2-s sample, could have enhanced stimulus control by the keylight colors while reducing stimulus control by the sample durations. The net effect could be a strong tendency to choose red *regardless of sample duration*, a generalized bias for red that would have increased correct responses following the 2-s sample and decreased correct responses following the 6-s sample—the trade-off revealed in [Figure 5](#). This competitive dynamic may also involve some degree of hysteresis because reinforcement for choosing red seems to become more effective *for several sessions* (more than 10 in [Figure 5](#)) than reinforcement for choosing green.

This account of acquisition trade-offs is speculative, but its emphasis on extinction seems consistent with another finding. For some pigeons and phases, performance at the currently long sample (6 s when the samples were 2 s and 6 s; 18 s when they were 6 s and 18 s) decreased during the generalization test sessions, even though correct responses continued to be reinforced. Pigeon P273 from the absolute-downshift group showed the clearest example. In the generalization test session of Phase B (see [Figure 5](#)), P("Green") after the 6-s sample equaled .43, a value noticeably below the proportions observed in the previous (.76) and following (.93) sessions (see also [Figure 2](#), both pigeons in Phase A, and Pigeon P762 in Phases B and A'; [Figure 3](#), both pigeons in Phase B; [Figure 4](#), Pigeon P229 in Phases A and A'). This test effect explains why we described the resulting gradient not as "peak-shift" but as "peak-shift-like": The higher value of P("Green") at a sample different from the trained sample seemed to be related to the disruption of performance at the trained sample and not only to a shift in the duration that yields the highest probability of responding "Green."

Alternatively, we could interpret the peak-shift-like effect in terms of adaptation-level theory (see [Thomas, 1993](#)). Assume that training with 2s→Red, 6s→Green sets the pigeon's adaptation level (AL) at the geometric mean, 3.5 s. The pigeon would then associate the samples perceived as below that level (2 s) with red, and those perceived as above (6 s) with green. If, during testing, the AL increased to the geometric mean of all samples, 4.7 s, the discriminability of the 6-s sample would decrease and that of the 2-s sample would increase, although the latter effect would be hard to detect because of a ceiling effect. Testing after training with the 6-s and 18-s samples would yield a similar result.

Our data were partly consistent with the account. The number of correct responses after the 6-s sample was, on average, 8.4% (≈ 2.5 trials out of 30) less during the generalization test sessions than during the two sessions that preceded and followed them (matched-pair t test, $t[7] = 7.97$, $p < .001$, $d = 2.8$, 95% CI [1.2, 4.4]). However, the decrease was much stronger when 6 s was trained with 2 s than with 18 s (27% vs. 6.7%; $t[7] = 2.6$, $p < .05$, $d = 0.91$, 95% CI [0.05, 1.72]), an asymmetry not predicted by

AL. Moreover, it is also unclear how to derive the inverted V-shaped gradients from the AL theory.

Future research should investigate these alternative accounts, how extinction may trigger acquisition trade-offs or disrupt performance during generalization tests, particularly following long samples, and how new samples may change the pigeon's AL. Clarifying these issues may help us understand better the absolute/relative nature of stimulus control in the bisection task.

We conclude with some thoughts about the original questions: Which group, relative or absolute, learns the bisection tasks faster? And, more broadly, is stimulus control in the temporal bisection task absolute or relational? The answer to the first question depends on whether we focus on the 6-s sample (advantage of the absolute group) or both samples (advantage of the relative group). More decisively, perhaps, because the acquisition curves from the two groups followed distinctly different patterns at each phase transition, the question of which group learns faster is, if not devoid of theoretical interest, at least secondary to our understanding of these patterns.

Concerning the second question, given that a Spencean model such as LeT predicted the major trends in the data, we conclude that the current data in the temporal bisection task remains consistent with the absolute (null) hypothesis. However, our conclusion must be tempered by three factors: the relatively small number of pigeons included in the present study, the occasional peak-shift-like effects that seem consistent with AL's relational account, and the fact that other studies have shown that pigeons respond relationally when explicitly trained to do so with multiple pairs of samples (e.g., Dreyfus, 1992; Fetterman & Dreyfus, 1986). Whether relational responding in the bisection tasks occurs with more training, or training with more than two pairs of samples, remains an open question. If this proves to be the case, then the challenge will be to articulate how the two forms of responding, absolute and relational, actually combine.

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- To select the appropriate reviewers for each manuscript, the editor needs detailed information. Please include with your letter your vita. In the letter, please identify which APA journal(s) you are interested in, and describe your area of expertise. Be as specific as possible. For example, “social psychology” is not sufficient—you would need to specify “social cognition” or “attitude change” as well.
- Reviewing a manuscript takes time (1–4 hours per manuscript reviewed). If you are selected to review a manuscript, be prepared to invest the necessary time to evaluate the manuscript thoroughly.

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