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RELATIVE VERSUS ABSOLUTE STIMULUS CONTROL IN THE TEMPORAL BISECTION TASK

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When subjects learn to associate two sample durations with two comparison keys, do they learn to associate the keys with the short and long samples (relational hypothesis), or with the specific sample durations (absolute hypothesis)? We exposed 16 pigeons to an ABA design in which phases A and B corresponded to tasks using samples of 1 s and 4 s, or 4 s and 16 s. Across phases, we varied the mapping between the samples and the keys. For group Relative, short and long samples were always associated with the same keys (e.g., Phase A: '1s→ Left, 4s→ Right'; Phase B: '4s→ Left, 16s→ Right'); for group Absolute, the 4-s sample was associated always with the same key (e.g., Phase A: '1s→ Left, 4s→ Right'; Phase B: '16s→ Left, 4s→ Right'). If temporal control is relational, group Relative should learn the new task faster than group Absolute, but if temporal control is absolute, the opposite should occur. We compared the results with the predictions of the Learning-to-Time (LeT) model, which accounts for temporal discrimination in terms of absolute stimulus control and stimulus generalization. The acquisition curves of the two groups were generally consistent with LeT and therefore more consistent with the absolute than the relative hypothesis.

Key words: relative versus absolute, LeT model, stimulus control, timing, pigeon

In the present study, we examine the issue of absolute versus relative stimulus control in the time domain. Can temporal control be relational, and, in the affirmative, under what circumstances and through what processes? To elaborate the issue, consider a prototypical temporal discrimination task, the bisection task. On each trial, a rat is presented with one of two sample stimuli, for example, a houselight illuminated for 1 s or 4 s. Following the sample, the rat is given a choice between two comparison stimuli, a left lever and a right lever. Choices of the left lever are reinforced following the 1-s samples, and choices of the right lever are reinforced following the 4-s samples. We represent these reinforcement contingencies by the mapping '1s→Left, 4 s→Right'. After a dozen sessions or so, the rat responds correctly on more than 90 per cent of the trials. What did the rat learn?

The Absolute Hypothesis states that the rat learned an absolute discrimination, to choose one or the other lever based on one or the other absolute duration of the sample. Moreover, the choice of one lever is not restricted to a specific duration but generalizes to adjacent durations (stimulus generalization). In contrast, the Relational Hypothesis states that the rat learned the relation between the stimulus durations; in particular, that the Left choice is reinforced following the shorter stimulus, and the Right choice is reinforced following the longer stimulus. A third hybrid hypothesis is also possible—the rat may have learned to choose the levers on the basis of both the absolute and the relative stimulus durations—but for clarity we will continue to stress the two pure hypotheses.

Two studies have claimed evidence for relational control in bisection tasks. Zentall, Weaver and Clement (2004) exposed pigeons to the following mappings '2s→Red, 8s→Green' (first bisection task with red and green keylights as comparisons) and '4s→Vertical, 16s→Horizontal' (second bisection task with a vertical or a horizontal white bar projected on a dark key as comparisons). Critically, in the first task, the long duration of 8 s equaled the geometric mean of the durations used in the second task (i.e., $8 = \sqrt{[4 \times 16]}$) and, conversely, in the second task, the short duration of 4 s equaled the geometric mean of the durations used in the first task ($4 = \sqrt{[2 \times 8]}$). The reason to choose these specific values relies on a robust empirical finding obtained in timing studies, name-

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ly, that the point of subjective equality of two durations is their geometric mean (Catania, 1970; Church & Deluty, 1977; Gibbon, 1981, 1991; Gibbon, Church, & Meck, 1984; Killeen & Fetterman, 1988; Platt & Davis, 1983; Stubbs, 1968). After learning the two bisection tasks, the pigeons received two types of test trials. On one type, they chose between the Red and Green comparisons following 4-s test samples; on the other type, they chose between the Vertical and Horizontal comparisons following 8-s test samples. According to Zentall et al. (2004), the Absolute Hypothesis predicted indifference on both test trials because the sample duration equaled the geometric mean of the training durations associated with the comparison stimuli. However, the Relational Hypothesis predicted a preference for Red over Green on the first type of test trial and a preference for Horizontal over Vertical on the second type of test trial. The predictions follow because, according to the Relational Hypothesis, the pigeons learned during the second task that the 4-s sample was the short sample, and, during the first task, that after the short sample choosing Red was reinforced; hence the preference for Red after the 4-s test samples. Similarly, the pigeons learned during the first task that the 8-s sample was the long sample, and, during the second task, that after the long sample choosing Horizontal was reinforced; hence the preference for Horizontal following the 8-s test samples. The results were consistent with the Relational Hypothesis—the pigeons preferred the Red key after 4-s samples and the Horizontal key after the 8-s samples, although only the former effect was statistically significant.

Maia and Machado (2009) reproduced Zentall et al.'s (2004) study but used more sample durations during the test trials so that full psychometric functions relating preference for Red and Horizontal to sample duration could be plotted. Their results were inconsistent with the Relational Hypothesis but consistent with the Absolute Hypothesis, because preference for Red after 4-s samples did not differ significantly from preference for Horizontal after 8-s samples. Similarly, when Russell and Kirkpatrick (2007) tested the absolute versus relational account of bisection with a more complex procedure—rats learned to associate three stimulus durations with two or three responses—they obtained results more consistent with the Absolute than the Relative Hypothesis.

The other study that addressed the Relative versus Absolute issue in the bisection task followed a different approach. Church and Deluty (1977) trained one group of 4 rats in the bisection task '1s→Left, 4s→Right'. Next, they divided the rats into a Relative group and an Absolute group, and each group learned a second bisection task involving sample durations of 4 s and 16 s. The Relative group learned the mapping '4s→Left, 16s→Right', which retains the relational structure of the first task because the Left and Right levers remain the correct choices after the short and long samples, respectively. The Absolute group learned the reverse mapping '4s→Right, 16s→Left', which retains (part of) the absolute structure of the first task because the Right lever remains the correct choice after the common, 4-s sample. To summarize, the experiment involved training the rats in two bisection tasks, the second of which preserved either the relative or the absolute mapping of the first. At issue was which group would learn the second task faster.

The results showed that the proportion of correct choices following the 4-s samples increased faster in group Relative than in group Absolute. In fact, somewhat surprisingly, accuracy in the Absolute group remained below 75% even after 15 training sessions. Church and Deluty's (1977) results suggested that preserving the relative mapping 'short→ Left, long→Right' enhanced learning, which is more consistent with the Relational Hypothesis (see Church & Deluty for more experimental details and data interpretation).

Important as it was for our understanding of temporal discrimination in general and temporal bisection in particular, Church and Deluty's (1977) study has a few shortcomings. First, no data were reported concerning performance on trials in which 16-s and 1-s sample stimuli were presented. If the Relative and Absolute groups differed also in the speed of acquisition of the 16-s or 1-s discriminations, then we may need to revise our conclusions concerning the Absolute versus Relative issue.

Second, before the experiment described above, all 8 rats had been exposed to another temporal discrimination task ('2s→Left, 8s→Right') and this fact may help explain the differences between the two groups. On the one hand, when we consider the three mappings learned by each group—one with 2-s and 8-s samples, one with 1-s and 4-s samples, and one with 4-s and 16-s samples—we realize that whereas for group Relative the second and third mappings preserved the relational structure of the previous mapping, for group Absolute the second mapping preserved the relational structure of the first mapping, but the third mapping preserved the absolute structure of the second mapping. That is, group Relative had a consistent history, but group Absolute did not. On the other hand, the results could reflect also the differential effects of the generalization gradients induced by the 2-s versus 8-s training on the acquisition of the third discrimination. In either case, the '2 s versus 8 s' previous task confounds the interpretation of the data. Finally, it is also the case that Church and Deluty's (1977) study has never been replicated with either the same or a different species. Hence, the robustness and generality of their findings remain uncertain.

The first goal of the present study was to improve Church and Deluty's (1977) study and extend it to another species. We exposed 16 pigeons to an ABA design in which Phases A and B corresponded to bisection tasks with different pairs of sample durations (1 s and 4 s, or 4 s and 16 s) and different stimulus–response mappings (e.g., "1s→Left, 4s→ Right"). For half of the birds, the task learned in Phase B and the second Phase A (henceforth, A′) preserved the relational mapping of the task learned in Phase A (group Relative); for the other half, the task learned in Phases B and A′ preserved part of the absolute mapping of the task learned in Phase A (group Absolute). In addition, within each group, half of the birds learned first the task with the 1-s and 4-s samples and next the task with the 4-s and 16-s samples (group Upshift), and the other half learned the two tasks in reverse order (group Downshift). By comparing the acquisition curves for the common (4-s) sample and the other (1-s or 16-s) samples in groups Relative and Absolute during Phases B and A′, we expected to gain a deeper understanding of the Relational versus Absolute form of stimulus control in the bisection task.

The Absolute versus Relational issue is also important to test theoretical models of timing. Hence, the second goal of the present study was to test one of these models, the Learning-to-Time (LeT) model (Machado, 1997; Machado, Malheiro, & Erlhagen, 2009). We focus on LeT because, in contrast with other models such as Scalar Expectancy Theory (SET, e.g., Gibbon, Church, & Meck, 1984), the Behavioral Theory of Timing (BeT, e.g., Killeen & Fetterman, 1988), or the Behavioral Economic Model (BEM, e.g., Josefowiez, Staddon, & Cerutti, 2009), LeT makes specific predictions concerning acquisition and phase transitions. In addition, as we explain below, the LeT model is a clear instantiation of the Absolute Hypothesis.

The LeT model—general overview. Developed from earlier work by Killeen and Fetterman (1988), LeT assumes that temporal discrimination depends on three processes (see Figure 1 top), the activation of a set of behavioral states, the learning of associations between the states and the operant responses, and the selection of the choice response. We describe briefly how the model applies to temporal bisection and refer the reader to Machado et al. (2009) for quantitative details and applications to other temporal tasks.

According to LeT, when the sample is presented, a set of behavioral states is activated in series, first state 1, then state 2, and so on. The rate of activation of successive states remains constant within trials, but varies randomly across trials according to a Gaussian distribution with mean λ and standard deviation σ. At the end of the sample, one of the states is active, say, state n. That state is linked with the two operant responses, pecking the Left and Right keys, and the strengths of the two links, $W_{\mathrm{Left}}(n)$ and $W_{\mathrm{Right}}(n)$, determine the choice response. In fact, the probability of choosing the Left response equals $W_{\mathrm{Left}}(n)/[W_{\mathrm{Left}}(n)+W_{\mathrm{Right}}(n)]$. In addition, these links change with reinforcement and extinction according to a simple linear operator learning rule (Bush & Mosteller, 1955). The model uses five parameters: the mean (λ) and standard deviation (σ) of the speed of activation of the behavioral states, the extinction (α) and reinforcement (β) learning parameters, and the initial value of the associative links (W_0). In what follows, all parameters' values remained constant at $\lambda = 1.0$, $\sigma = 0.4$, $\alpha = 0.05$, $\beta = 0.04$, and $W_0 = 0.1$. These values were similar to the values used to fit bisection data

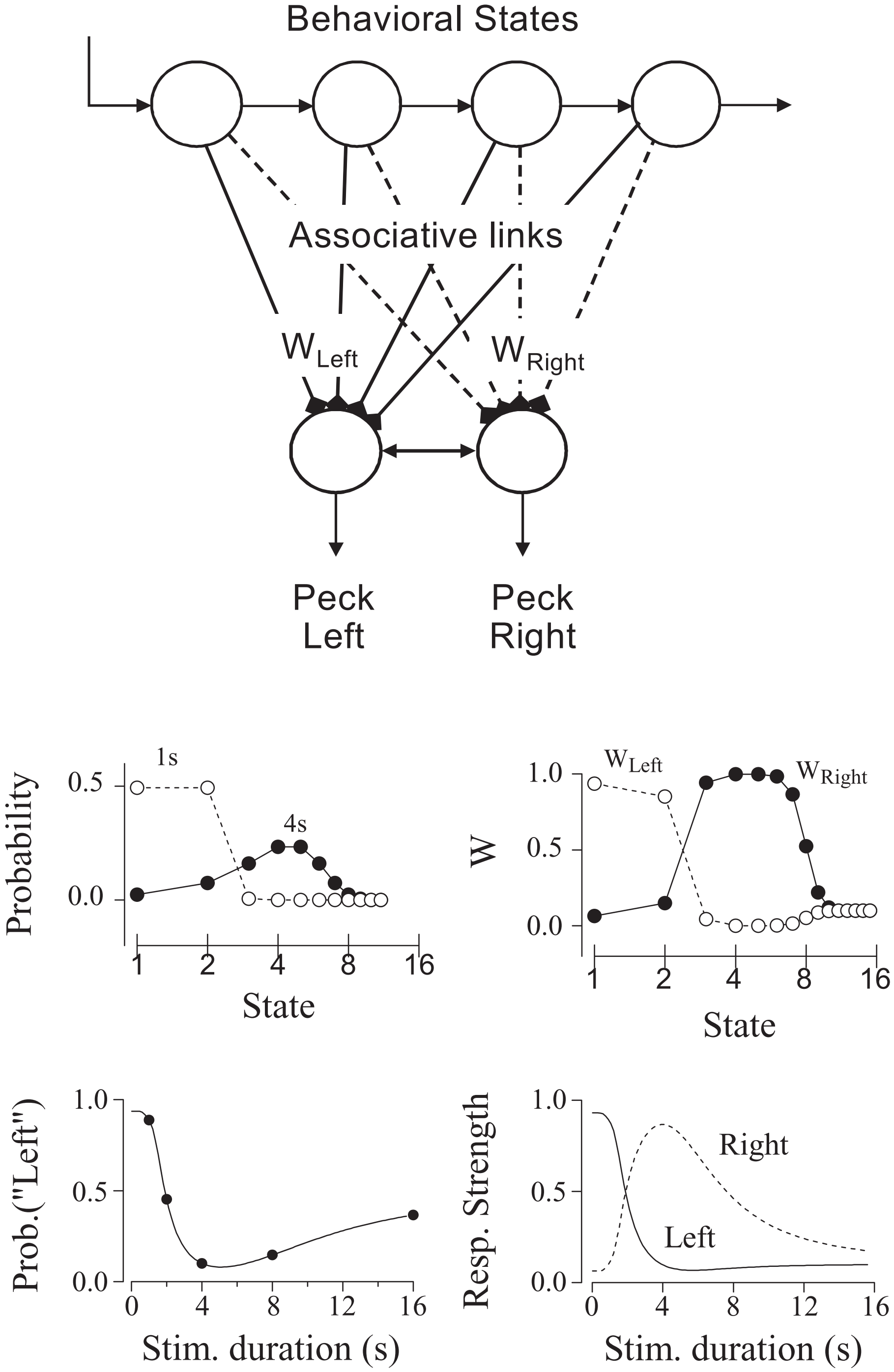

Fig. 1. Top. The structure of LeT. After a time marker, a set of states is activated in series. The states are coupled to various degrees (associative links) with the two responses. The strength of each response is determined by associative link of the state active at the end of a sample. Bottom. Simulation results for the task ‘1s→Left, 4s→Right’. The top left panel shows the probability that state n is active at the end of 1-s and 4-s samples. The top right panel shows the strength of the associative links connecting state n with the Left and Right responses. The bottom right panel shows the expected strengths of the Left and Right responses following samples of different durations. The bottom left panel shows the probability of responding Left as a function of sample duration.

in several previous studies (see Machado et al., 2009, for a summary), but other values could be used without changing significantly the model predictions.

Consider the bisection task '1s→Left, 4s→Right'. When a 1-s sample is presented, the active state at the end of the sample is likely to be one of the first states in the series. In fact, if we assume that successive states become active at the average rate of $\lambda = 1.0$ states per second (with $\sigma = 0.4$), then the first two states are the most likely to be active at the end of the 1-s samples. The open circles in the middle left panel of Figure 1 show the probability that state n (with $n \geq 1$) is active at the end of 1-s samples. Similarly, at the end of 4-s samples, the states most likely to be active are states number 4, 5, and neighboring states (filled circles). These state-activation curves, wider for 4-s samples than 1-s samples, are the basis of the temporal generalization gradients.

As the animal experiences the reinforcement contingencies, the associative links of the active states change. Thus, because Left choices are reinforced following 1-s samples, the links connecting the first states with the Left response will be strengthened and their values will approach 1 (see first two open circles in the middle right panel). In addition, because Right choices are extinguished following 1-s samples, the links between the first states and the Right response will be weakened and approach 0 (see first two filled circles). The two curves in the middle right panel show the effect of 20 sessions: States 1 and 2 are associated mostly with the Left response; states 3 to 8 are associated mostly with the Right response; and subsequent states, rarely active after 1-s or 4-s samples, maintain their initial link of $W_0 = 0.1$ with both responses.

Performance depends on the probability distribution of the active state and the profiles of associative links. Combined they determine both the strength of each response after a t-s sample (see bottom right panel) and the probability of choosing the Left key following a t-s sample (see bottom left panel). The former is akin to a temporal generalization gradient and the latter is the familiar psychometric function.

To recapitulate, when a 1-s sample is presented, one of the first two states is likely to be the active state (middle left panel) and because these states become associated mainly with the Left response (middle right panel), the strength of the Left response is greater than the strength of the Right response (bottom right panel) and the animal tends to choose Left (bottom left panel). Similarly, when a 4-s sample is presented, one of the next states (3 to 8) is likely to be the active state and because these states become associated mainly with the Right response, the animal tends to choose Right.

The LeT model—specific predictions. Let us first consider the case of the Relative Upshift and Absolute Upshift groups. The model predicts distinct acquisition and reacquisition curves for the two groups. Figure 2 shows the details. (Figures A1 and A2 in the Appendix may be consulted to understand the acquisition curves on the basis of the associative links at the end of each phase. Here we describe the qualitative patterns that will be used to compare the model with the data.)

The top panel corresponds to the Relative Upshift group and the bottom panel to the Absolute Upshift group. In each panel, the sets of data points from left to right show the proportion of correct responses in the last session of Phase A, in the first 10 sessions and in the last session of Phase B, and in the first 10 sessions and in the last session of Phase A′. Of particular relevance to the Relative versus Absolute issue are the acquisition curves during Phases B and A′. Three aspects of these curves are noteworthy. First, consistent with the Absolute Hypothesis, LeT predicts that, during the first sessions of Phase B, group Relative will perform poorly following the 4-s samples, whereas group Absolute will perform accurately following the same samples (compare filled circles in top and bottom panels during Phase B). The reason for the difference is that the states most active following the 4-s samples will have been associated with the Right response during Phase A, but during Phase B that response remains the correct response only for group Absolute. These predictions are the opposite of the results obtained by Church and Deluty (1977). Second, during the first sessions of Phase B, both groups will perform near chance following the 16-s samples (compare open squares in top and bottom panels) because the states active at the end of these samples will not have been active during the previous phase and

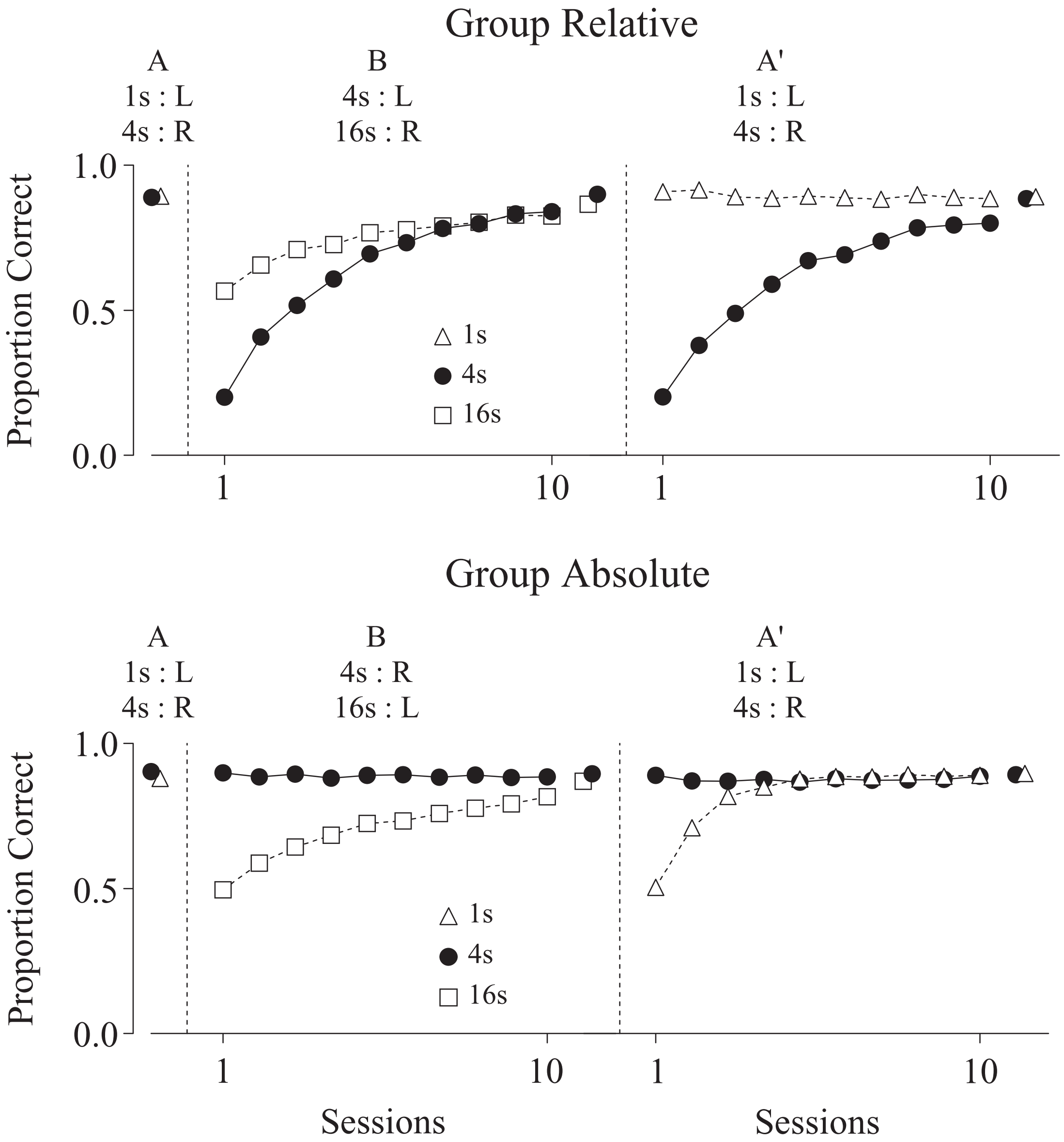

Fig. 2. Predictions of the LeT model for the Upshift groups. Top. Proportion of correct responses for group Relative following each sample (1 s, 4 s, or 16 s) at the end of Phase A, during the first 10 sessions and at the end of Phase B, and during the first 10 sessions and at the end of Phase A'. Bottom. Corresponding predictions for group Absolute. The dotted vertical lines separate experimental phases.

therefore they maintain their initial link strength. Behaviorally one could say that 16 s is practically outside the basin of the 4-s generalization gradient established during the previous phase and therefore the animal remains indifferent between the two choices. Church and Deluty did not report choice proportions following the 16-s samples. Third, according to LeT the two groups will reach high accuracy levels on both samples, a prediction also at odds with Church and Deluty's findings.

During the first sessions of Phase A′, group Relative again will perform poorly following the 4-s samples but accurately following the 1-s samples. The reason for the latter is temporal generalization—the states that are active at the end of 1-s samples will have been active during some of the 4-s trials of Phase B and, on those trials, their association with the Left response will have been further strengthened. In other words, reinforcement of the "4s→Left" discriminated operant during Phase B will have generalized to 1 s and this generalization effect will contribute to correct performance on the "1s→Left" trials during Phase A′. According to LeT, then, we have here an interesting asymmetry: Whereas the "4s→Left" discrimination training in Phase B helps the "1s→Left" discrimination training in Phase A′, the "4s→Right" discrimination training in Phase A does not help the "16s→Right" discrimination training in Phase B. Generalization from 4 s to 1 s is substantially greater than from 4 s to 16 s. We will see another instance of this asymmetry below.

Concerning group Absolute, performance in Phase A′ following the 4-s samples will remain accurate, but performance following the 1-s samples will fall to chance, again because of temporal generalization—on some 4-s trials of Phase B, the states active after 1-s samples will have been active but, unlike for group Relative, on those occasions their links with the Left response will have been weakened. In other words, reinforcement on the "4s→Right" trials of Phase B will have generalized to 1s but this generalization effect will contribute to incorrect performance during Phase A′.

Figure 3 shows the model predictions for the Downshift groups. According to LeT, during Phases B and A′, group Relative (top panel) will perform poorly following the 4-s samples, whereas group Absolute (bottom panel) will perform accurately following the same samples. The reasons are the same as for the Upshift groups. Concerning the 1-s and 16-s samples, group Relative will perform accurately following either sample, but group Absolute will perform poorly following the 1-s samples during the first sessions of Phase B, and accurately following the 16-s samples throughout Phase A′. The difference between the 1-s and 16-s acquisition curves is another instance of the asymmetry mentioned above, that generalization from 4 s to 1 s is substantially greater than from 4 s to 16 s. In this case, the "4s→Left" discrimination training during Phase A harms the "1s→Right" discrimination training during Phase B, but the "4s→Left" discrimination training during Phase B does not harm the "16s→Right" discrimination training during Phase A′.

To summarize, a) performance following the 4-s samples is always disrupted in group Relative, but never disrupted in group Absolute; b) performance following the 1-s and 16-s samples is either equal in the two groups or better in group Relative; and c) due to differences in the degree of overlap between the generalization gradients of 1 s, 4 s, and 16 s, performance following the 1- or 16-s samples differs between the Upshift and Downshift groups. The model's predictions offer a clear standard against which experimental results may be compared.

METHOD

Subjects

Sixteen pigeons (*Columba livia*) participated in the experiment. They were housed individually in a colony room with a 12:12-hr light: dark cycle with lights on at 8:00 am. Throughout the experiment the pigeons were maintained at 80% of their free-feeding body weight, with free access to water and grit in their home cages. Seven pigeons (P068, P093, P236, P572, P665, P795, and P816) were experimentally naïve, and the remaining 9 had experimental histories unrelated to temporal bisection tasks.

Apparatus

The experiment used five standard operant chambers from Med Associates, each equipped with three keys and a feeder on the intelligence panel. The keys measured 2.5 cm in diameter, were arranged in a row, 18.5 cm from the floor grid, centered on the panel, and 9 cm apart, center to center. The central key could be illuminated with a white light and the side keys could be illuminated with a red light. The 6 × 5-cm feeder opening was located below the central key, 3.5 cm above the floor grid. A 7.5-W light illuminated the mixed grain when the feeder was activated. On the back panel of the chamber, a 7.5-W houselight provided general illumination. The operant chamber was enclosed by an outer box that contained a fan to circulate air and help to mask extraneous noises. A personal computer programmed in Visual Basic 2005 controlled

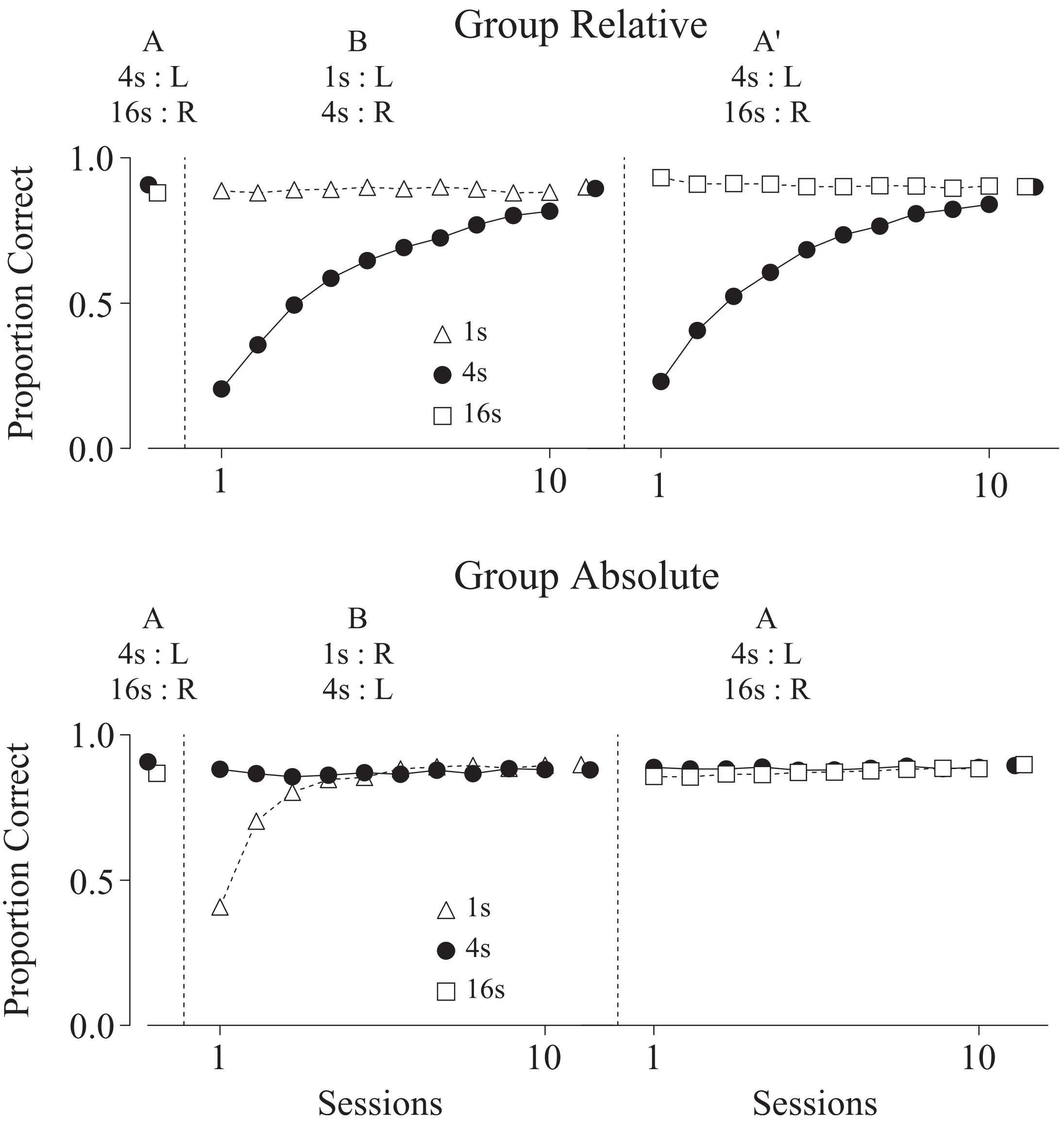

Fig. 3. Predictions of the LeT model for the Downshift groups. Top. Proportion of correct responses for group Relative following each sample (1 s, 4 s, or 16 s) at the end of Phase A, during the first 10 sessions and at the end of Phase B, and during the first 10 sessions and at the end of Phase A'. Bottom. Corresponding predictions for group Absolute. The dotted vertical lines separate experimental phases.

the experimental events and recorded data. The program interfaced with the Whisker software (Cardinal & Aitken, 2010) to communicate with the chambers and time events with a resolution of 1 ms.

Procedure

After the birds learned (or relearned) through autoshaping to peck the side keys, illuminated with red light, the experiment began. Each session consisted of 60 trials separated by a dark 30-s ITI. Each trial began with the simultaneous illumination of the houselight and the center key with white light. After the sample duration elapsed, the center key was turned off and the side keys were illuminated with red light. Pecking on either side key turned both keylights off. If the

Table 1

Experimental design. Four groups (Relative Upshift, Absolute Upshift, Relative Downshift, and Absolute Downshift) were exposed to an ABA design. In the three rightmost columns, each cell shows the two sample durations. The left sample was assigned to the Left key and the right sample to the Right key.

			Phase		
Trend	Mapping	Pigeon	A	B	A′
Upshift	Relative	PG26	1–4	4–16	1–4
		P572	1–4	4–16	1–4
		P508	4–1	16–4	4–1
		P068	4–1	16–4	4–1
	Absolute	P876	1–4	16–4	1–4
		P435	1–4	16–4	1–4
		P795	4–1	4–16	4–1
		P236	4–1	4–16	4–1
Downshift	Relative	P434	4–16	1–4	4–16
		P454	4–16	1–4	4–16
		P053	16–4	4–1	16–4
		P665	16–4	4–1	16–4
	Absolute	P877	4–16	4–1	4–16
		P093	4–16	4–1	4–16
		P784	16–4	1–4	16–4
		P816	16–4	1–4	16–4

choice was correct, the feeder was raised for an individually adjusted duration (range 2 to 6 s) and then the ITI started; if the choice was incorrect, the ITI started immediately and the trial was repeated (correction method). During the first session, whenever a trial was repeated, only the correct comparison key was presented after the sample. During the second session, after two consecutive errors, only the correct comparison key was presented. From the third session onward, after three consecutive errors, only the correct comparison key was presented. With this arrangement we intended to promote learning while simultaneously reducing the number of correction trials, particularly during the first sessions of each phase. Correction trials were never included in the data analyses.

The pigeons were divided into four groups and each group was exposed to three phases according to an ABA design. Table 1 shows the details. Half of the pigeons learned first the discrimination involving the short samples of 1 s and 4 s (Upshift) and the other half learned first the discrimination involving the long samples of 4 s and 16 s (Downshift). Within each of these groups, half belonged to the Relative group and the other half belonged to the Absolute group. The two numbers in each cell of Table 1 represent the sample duration assigned to the Left and Right keys, respectively. Thus, as Table 1 shows, the correct choice following each sample was fully counterbalanced across birds. Sessions ended after 30 presentations of each sample (excluding correction trials) in random order.

Each phase continued until a) the proportion of correct choices following each sample equaled at least 90 % for three consecutive sessions, and b) a minimum number of sessions had taken place (15, 20, and 10 for Phases A, B, and A′, respectively). The number of training sessions remained similar to that used by Church and Deluty (1977).

RESULTS

All pigeons learned the discriminations. They required 17.4 sessions on average to complete Phase A (range: 15–24), 20.1 for Phase B (range: 11–25[1]), and 10.8 for Phase A′ (range: 10–15).

Figure 4 shows the average data for the Upshift pigeons (the tables in the Appendix may be consulted for the individual data). The top and bottom panels correspond to the Relative and Absolute groups, respectively. For group Relative, proportion correct following the 4-s samples decreased to chance in Phase B and below chance in Phase A′ and then, in both cases, it increased. Concerning the other sample, in Phase B, proportion correct following the 16-s samples started slightly above chance and tended to be higher than proportion correct following the 4-s samples. In Phase A′ proportion correct following the 1-s samples remained as high as in Phase A. The overall pattern of results for this group is consistent with LeT (compare the top panels of Figures 2 and 4).

For group Absolute, in Phase B, proportion correct decreased to chance following the 4-s samples and started at chance following the 16-s samples. In both cases, it then increased. During Phase A′, proportion correct following 1-s samples decreased to chance and then increased rapidly, whereas following 4-s samples it remained relatively high. The overall pattern of results is only partially consistent

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[1] One pigeon was accidentally moved to Phase A′ after 11 sessions, although its proportion correct following each sample was above 90% during the last three sessions of Phase B.

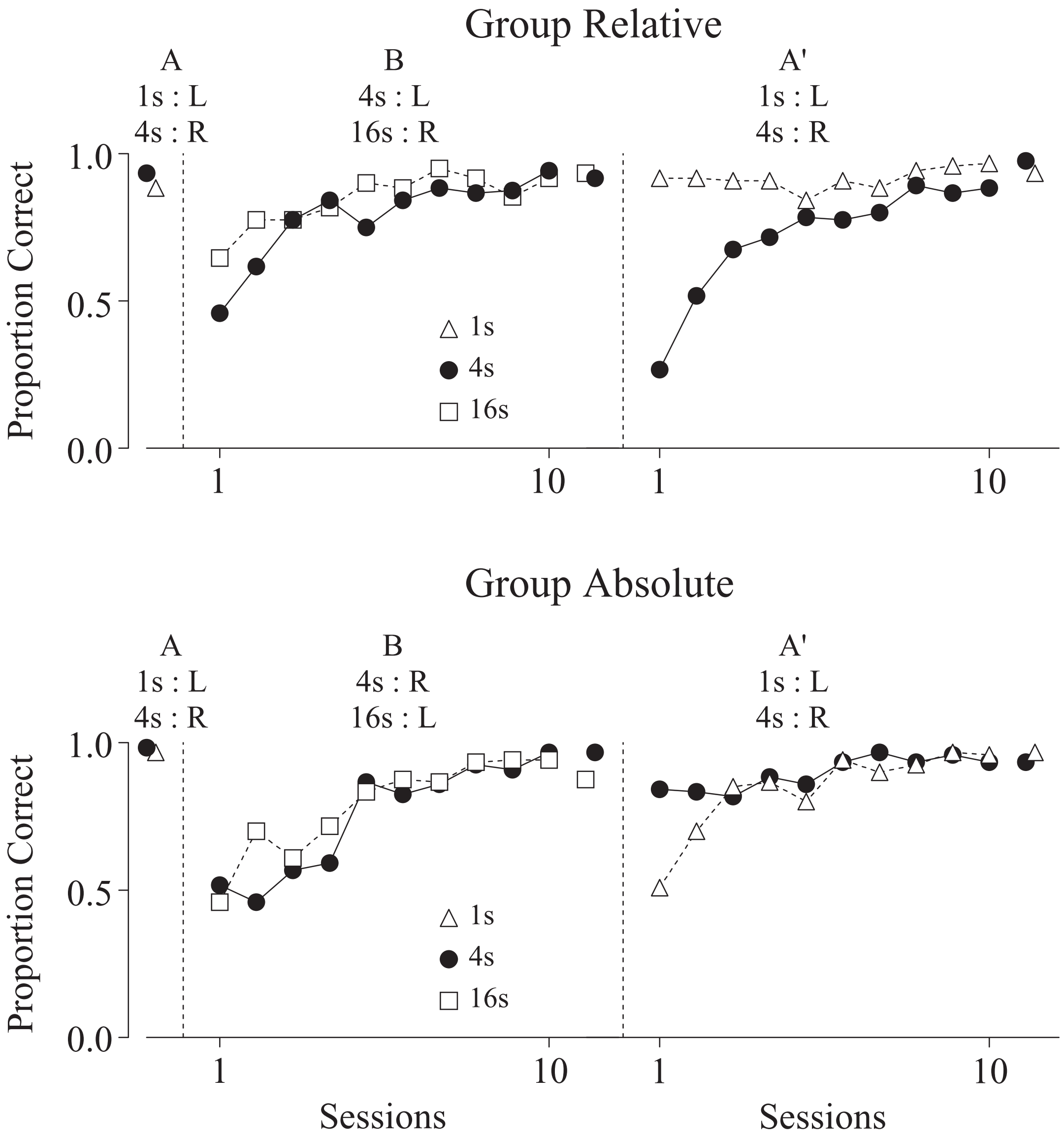

Fig. 4. Obtained results for the Upshift groups. Top. Proportion of correct responses for group Relative following each sample (1 s, 4 s, or 16 s) at the end of Phase A, during the first 10 sessions and at the end of Phase B, and during the first 10 sessions and at the end of Phase A'. Bottom. Corresponding results for group Absolute. The dotted vertical lines separate experimental phases.

with LeT. The major discrepancy between data and model is the severe disruption of performance following the 4-s samples during Phase B, which the model did not predict (compare the bottom panels of Figures 2 and 4).

Figure 5 shows the average data for the Downshift pigeons. For group Relative, proportion correct following the 4-s samples decreased significantly in the first session of Phases B and A′ and then it increased with training. Proportion correct following the 1-s samples in Phase B started significantly above chance, and following the 16-s samples in Phase A′ remained as high as in Phase A. For group Absolute, proportion correct following the 4-s samples decreased slightly in the beginning of Phases B and A′. Concerning the other samples, in Phase B, proportion correct follow-

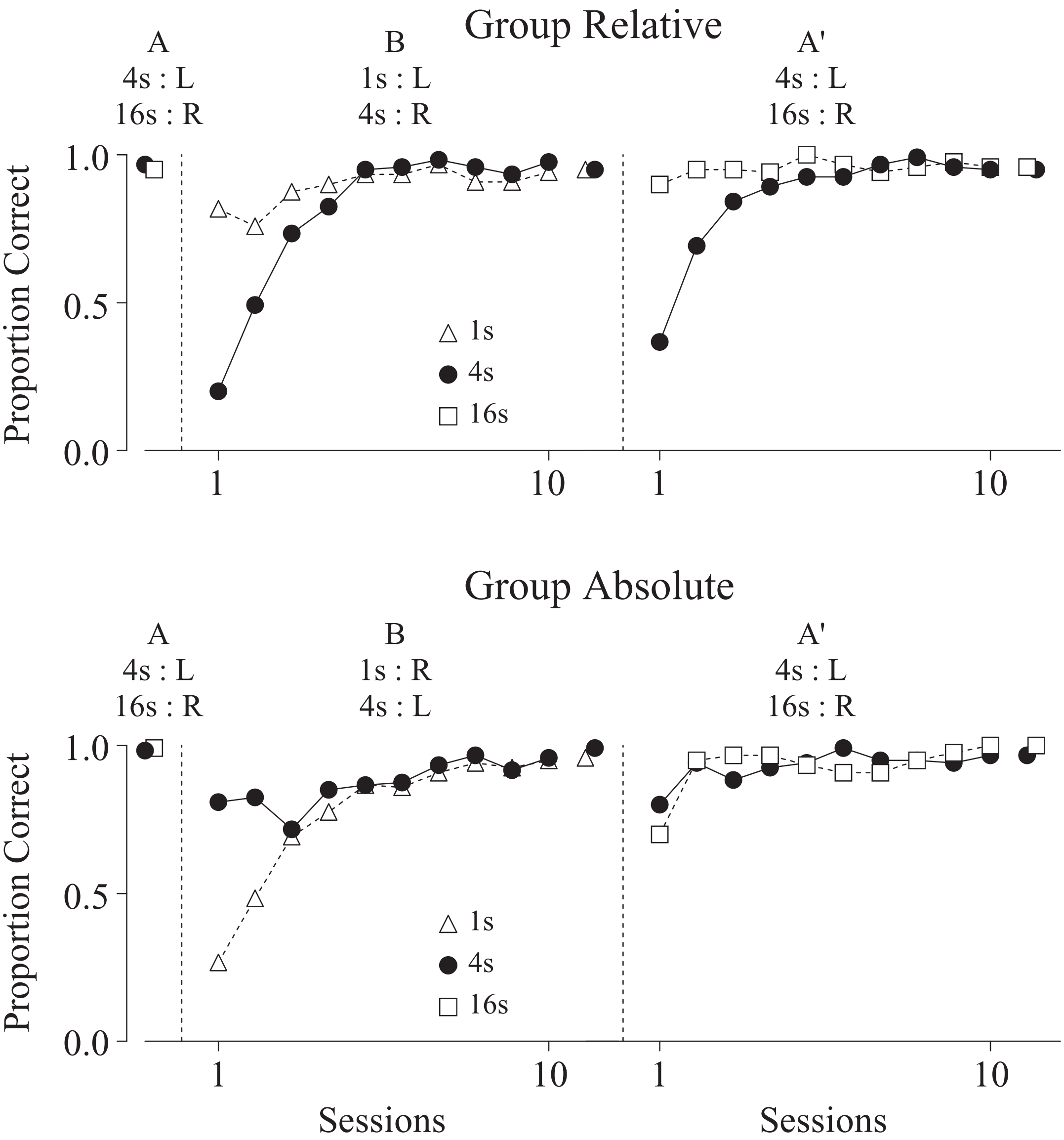

Fig. 5. Obtained results for the Downshift groups. Top. Proportion of correct responses for group Relative following each sample (1 s, 4 s, or 16 s) at the end of Phase A, during the first 10 sessions and at the end of Phase B, and during the first 10 sessions and at the end of Phase A′. Bottom. Corresponding results for group Absolute. The dotted vertical lines separate experimental phases.

ing the 1-s samples started significantly below chance and then it increased, whereas in Phase A′, proportion correct following 16-s samples decreased slightly with respect to Phase A. The overall pattern of results for the Downshift pigeons is consistent with LeT (compare Figures 3 and 5).

To assess the statistical significance of the foregoing results, we conducted mixed ANOVAS with Mapping (Relative vs. Absolute) or Trend (Upshift vs. Downshift) as the between-subjects factors and Session (10 levels for the first 10 sessions) as the within-subjects factor. To better understand the ANOVA results, Figure 6 re-plots the acquisition curves in a different way. The left and right panels show the acquisition curves for Phases B and A′, respectively, and the top, middle, and bottom panels show the acquisition curves for the 4-s, 1-s, and 16-s samples, respectively. The inset graphs show the model predictions. Consider the 4-s samples. According to LeT, the 2 × 2 x 10 mixed ANOVA should yield the following significant effects: a) main effect of Mapping because overall the Absolute groups (unfilled symbols) should perform better than the Relative groups (filled symbols); b) a main effect of Session because proportion correct should increase with learning; and, more importantly, c) an interaction between Session and Mapping because the Relative groups should start near indifference and then learn across sessions, whereas the Absolute groups should start at a high value and maintain accurate performance across sessions. For Phase B, the ANOVA yielded only part of the predicted pattern of results, significant effects of Session, $F(9, 108) = 35.1$, $p < .001$ and Session x Mapping, $F(9, 108) = 5.28$, $p < .001$, but not of Mapping, $F(1,12) = 0.35$; the other effects also were not significant except the three-way interaction Session x Mapping x Trend, $F(9, 108) = 5.71$, $p < .001$. The reason for the three-way interaction is that the acquisition curves of the Relative and Absolute groups differed between the Upshift and Downshift conditions. For Phase A′, the ANOVA yielded the predicted pattern of results, significant main effects of Sessions, $F(9, 108) = 20.8$, $p < .001$, Mapping, $F(1,12) = 9.08$, $p = .01$, and Sessions x Mapping, $F(9, 108) = 8.87$, $p < .001$; all remaining effects were not significant ($p > .05$).

Consider now the 1-s samples. According to LeT, the 2 × 10 ANOVA should yield significant effects of Session (overall improvement with training), Mapping (Relative better than Absolute), and, more importantly, Session x Mapping interaction (group Relative should show accurate performance across sessions, but group Absolute should start at indifference and then improve). The ANOVA for Phase B yielded the predicted pattern, significant effects of Session, $F(9, 54) = 14.2$, $p < .001$, Mapping, $F(1,6) = 17.95$, $p < .005$, and Session x Mapping, $F(9, 54) = 5.5$, $p < .001$. The ANOVA for Phase A′ yielded significant effects of Session, $F(9, 54) = 13.2$, $p < .001$ and Session x Mapping, $F(9, 54) = 10.1$, $p < .001$, but not of Mapping, $F(1,6) = 3.08$, $p = .13$.

With respect to the 16-s samples, LeT predicts that the 2 × 10 ANOVA for Phase B should yield a significant effect of Session, but no effect of Mapping or Session x Mapping. The ANOVA yielded the predicted pattern, for only the Session effect was significant, $F(9, 54) = 7.6$, $p < .001$. For Phase A′, LeT predicted no significant effects, not even of Session, because both groups should perform accurately from the first session onward. However, the ANOVA yielded a significant Session effect, $F(9, 54) = 2.7$, $p = .01$ because the first session yielded lower scores than the remaining sessions. In summary, the obtained statistical results were generally consistent with the predicted effects. The major exception occurred in Phase B with group Absolute Upshift following the 4-s samples.

The effects of the two phase transitions were stronger during the first session of each new phase. To better understand these effects, Figure 7 shows side by side the model predictions and the data (mean ± SEM) from the first session of Phase B (top four panels) and the first session of Phase A′ (bottom four panels). LeT (left panels) always predicts an interaction between sample duration and group such that, for group Relative, proportion correct at 4 s is lower than at the other sample duration, but the opposite is the case for group Absolute. The data showed the predicted interaction: The four between–within ANOVAS with Mapping as the between-subjects factor and Sample Duration as the within-subjects factor all yielded significant interactions at the .05 level. For group Relative performance was disrupted more following the 4-s sample than the other sample, whereas for Group Absolute the opposite was generally the case. The major discrepancy between model and data occurred during Phase B in the Upshift groups following the 4-s sample (compare top two panels in Figure 7).

The data also revealed differences between the Upshift and Downshift groups, particularly during Phase B. The relevant comparisons are indicated by corresponding letters in the top two panels of Figure 7. As letter a shows, proportion correct following 4-s samples was higher in group Relative Upshift (.46) than in group Relative Downshift (.20; $t(6) = 2.79$, $p = 0.02$). Similarly, the letter b shows that proportion correct following 4-s samples was lower in group Absolute Upshift (.52) than in group Absolute Downshift (.81; $t(6) = 2.22$, $p = .03$). These differences are not predicted by LeT.

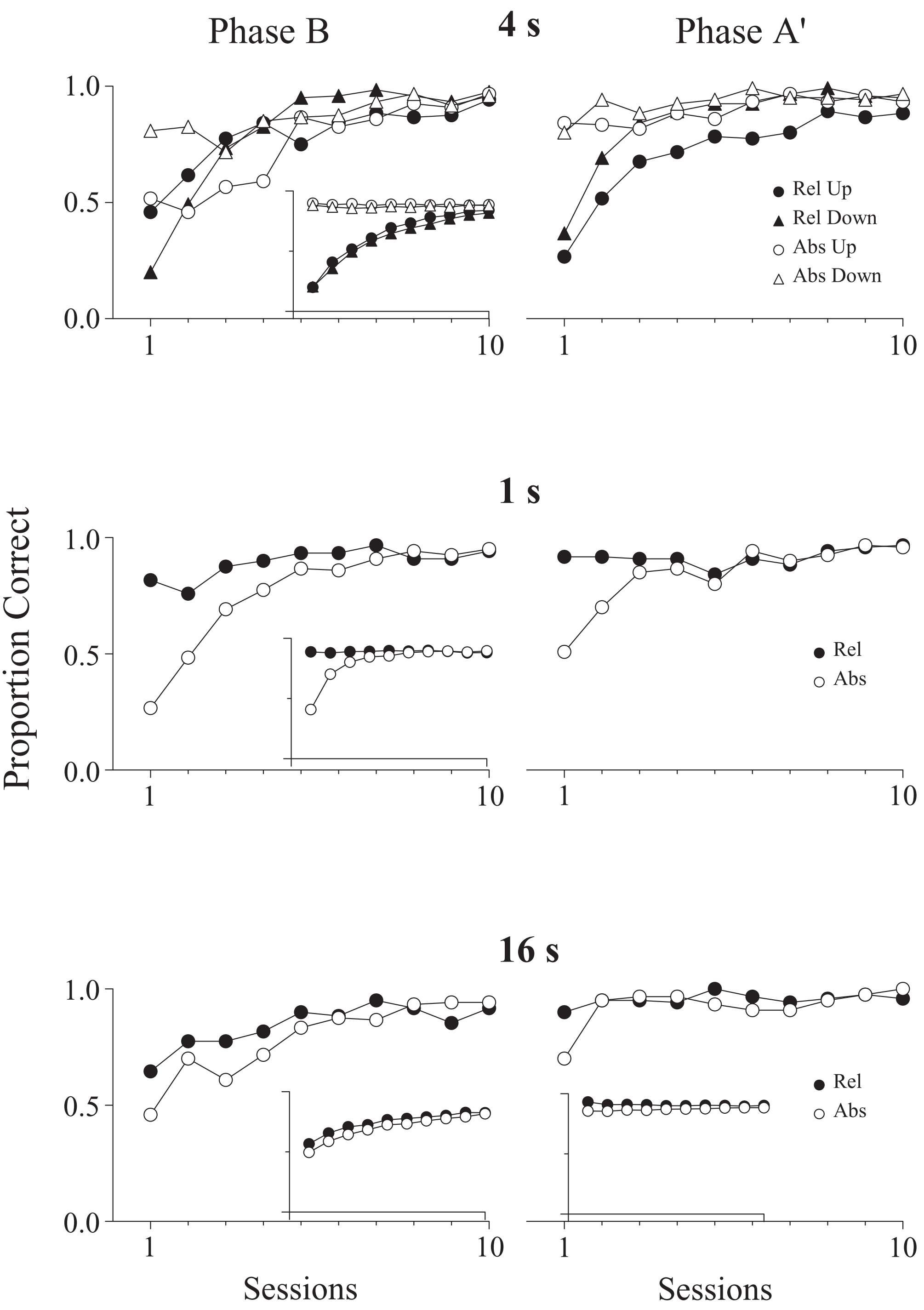

Fig. 6. Average acquisition curves for phases B (left panels) and A′ (right panels) following the 4-s samples (top), 1-s samples (middle), and 16-s samples (bottom). The inset graphs show the corresponding model predictions.

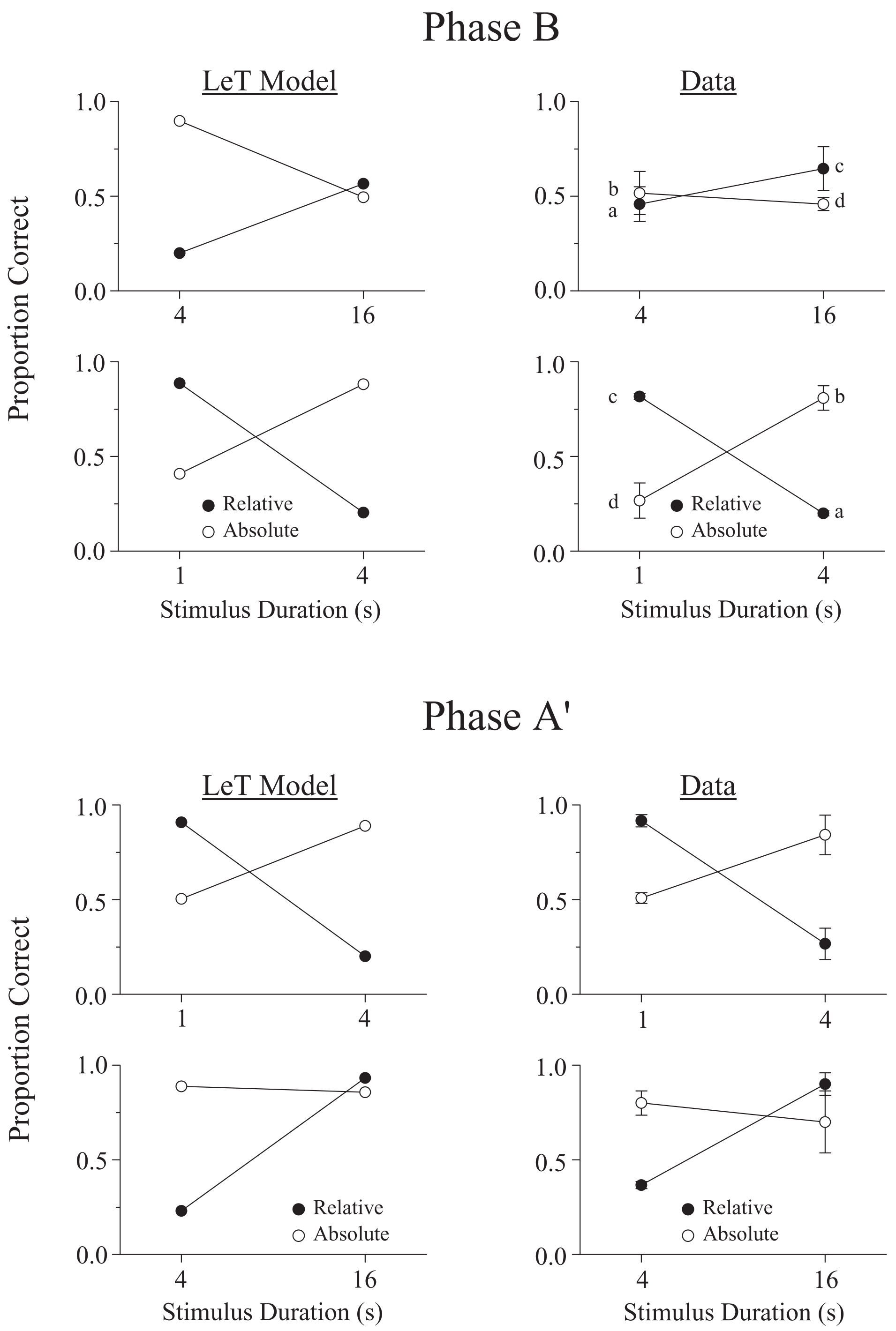

Fig. 7. Each row shows the predicted (left) and obtained (right) average proportions of correct responses (± SEM) as a function of sample duration for groups Relative and Absolute. The data come from the first session of Phase B (top four panels) and Phase A' (bottom four panels).

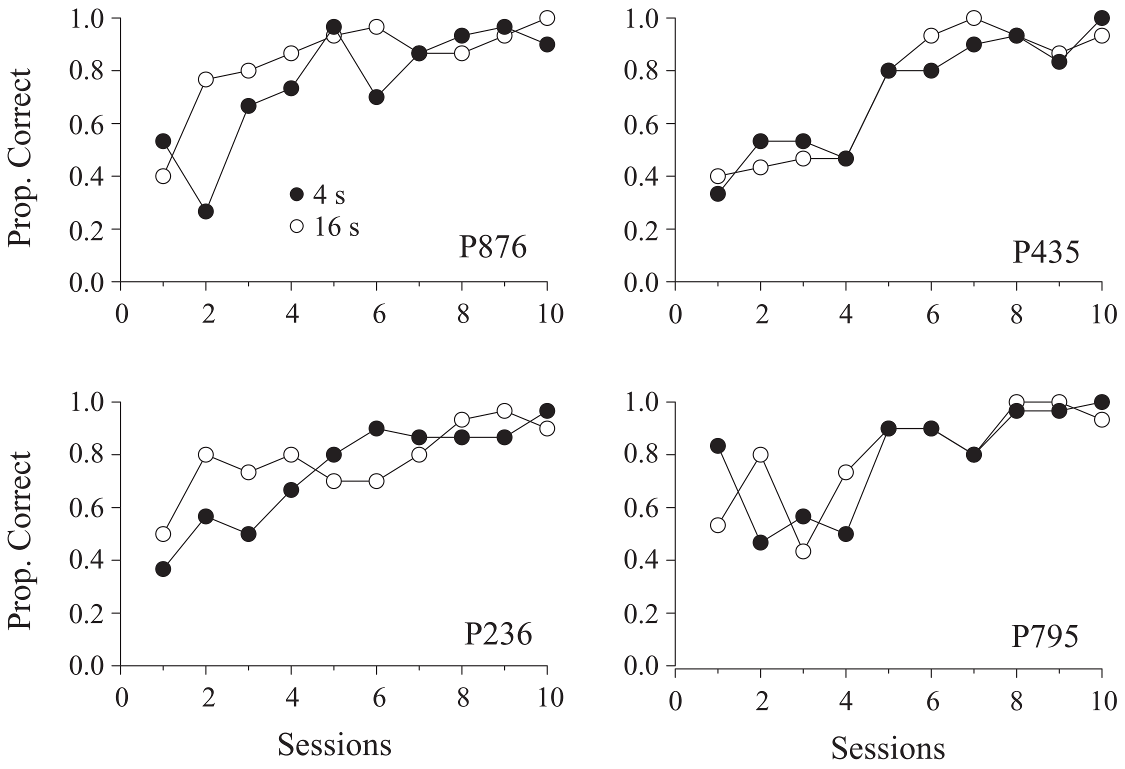

Fig. 8. Individual data for group Absolute Upshift during the first 10 sessions of Phase B. The symbols show proportion correct following 4-s and 16-s samples.

With the other samples, the differences between the Upshift and Downshift groups were similar but less reliable. Thus, as the letter c shows, proportion correct following 16-s samples in group Relative Upshift (.65) was lower than proportion correct following 1-s in group Relative Downshift (.82), but the difference was not statistically significant, $t(6) = 1.47$, $p = .1$). And as the letter d shows, proportion correct following the 16-s samples in group Absolute Upshift (.46) was higher than proportion correct following the 1-s samples for group Absolute Downshift (.27), but the difference was only marginally significant, $t(6) = 1.93$, $p = .05$). LeT predicts the same pattern of differences, although more extreme for the Relative groups and less extreme for the Absolute groups.

Most of our results were consistent with the Absolute Hypothesis as the LeT model instantiates it. The differences between the acquisition curves of the Relative and Absolute, Upshift and Downshift groups (Figures 4, 5, and 6), and the overall pattern of results during the first session of a new phase (Figure 7) were generally consistent with LeT. However, there was one major discrepancy, the severely disrupted performance of group Absolute Upshift following the 4-s samples, a result that LeT did not predict. Figure 8 shows the individual data for this group: 3 of the 4 pigeons showed disrupted performance on the 4-s samples in the first session and 1 (P795) showed it in the second session; performance on the 16-s samples started close to indifference, as LeT predicted. It was also the case that for pigeons P876 and P795, there seemed to be a negative covariation during the first sessions between proportion correct following 4-s samples and proportion correct following 16-s samples. We conclude that the major discrepancy between model and data was reliable across pigeons.

DISCUSSION

The present study investigated the issue of Relative versus Absolute stimulus control in the temporal bisection task. We first trained pigeons in one task and then compared how they learned two new tasks, one which maintained the mapping between relative sample durations and the two response keys, and one which reversed it. If the pigeons had learned the relational form of the first task, then they should learn the task that preserved it faster than the task that reversed it. On the other hand, if the pigeons had learned only the absolute form of the task, the opposite should be the case.

The present study improved and extended Church and Deluty's (1977) seminal work by changing the design from AB to ABA—a change that provided two occasions to obtain acquisition curves—simplifying the subjects' experimental history (i.e., no phase preceded Phase A), doubling the number of subjects in each group, analyzing the data in greater depth (e.g., we examined the results not only from the 4-s samples but also from the 1-s and 16-s samples), and extending the work to another animal species.

On a more theoretical note, the study also compared the data with the predictions of the Learning-to-Time (LeT) model. The model represents one way of instantiating the Absolute Hypothesis because it shows us what to expect if performance on the bisection task depends exclusively on stimulus generalization gradients (via state activation), and the learning of which key to choose following each sample duration (via associative links); nowhere in the model are sample stimuli represented or categorized relationally as short or long. Moreover, in contrast with other timing models (e.g., SET, BeT, BEM), LeT predicts not only steady-state performance but also acquisition. For these reasons, we consider LeT a plausible null hypothesis—only if the empirical evidence clearly rejects it will we entertain the arguably more complex Relational Hypothesis.

In what follows we summarize our empirical findings concerning the Relative and Absolute mappings as well as the Upshift and Downshift trends, compare these findings with the model's predictions and with Church and Deluty's (1997) results, and finally discuss their implications for the absolute versus relational issue in the time domain.

Relative versus absolute mappings. Our results showed that in group Relative, performance was always disrupted more following the common (4-s) sample than the other (1-s or 16-s) sample (Figures 4 and 5, top panels). In group Absolute, the opposite was generally, but not always the case; that is, performance following the 1-s or 16-s samples was generally disrupted more than performance following the 4-s sample (Figures 4 and 5, bottom panels). These effects were most clear during the first session of each new phase (Figure 7, right panels).

The foregoing results are partly consistent with LeT. On the one hand, LeT correctly predicts that performance will be disrupted mainly following the common sample in group Relative, and mainly following the other samples in group Absolute. On the other hand, the model did not predict the severe disruption in performance following the common sample in group Absolute Upshift. We return to this major discrepancy below.

LeT predicts a difference in the magnitude of the disruptions between the Relative and Absolute groups because these two disruptions have different causes. According to the model, group Relative chooses the wrong key following the 4-s sample because pecking that key was reinforced directly during the previous phase. More specifically, during the preceding phase the states most likely to be active at the end of the 4-s sample became strongly linked with the (now) incorrect key. In contrast, group Absolute chooses the wrong key following the 16-s or 1-s samples because of *initial conditions* (16-s samples) or *stimulus generalization* (1-s samples). When the 16-s samples are presented for the first time in Phase B (i.e., group Upshift), the animal makes incorrect choices on about 50% of the trials because the states that are active after 16 s did not become active during the 4-s trials of Phase A and for that reason they maintained their initial (and equal) associations with the two responses. But when the 1-s samples are presented for the first time in Phase B (i.e., group Downshift), the animal makes incorrect choices because the states that are active after 1 s became active during some of the 4-s trials of Phase A and on those trials the association with the (now) incorrect key was strengthened.

Because direct reinforcement biases the associative links more than stimulus generalization or the initial conditions, LeT predicts that the disruption following the 4-s sample in

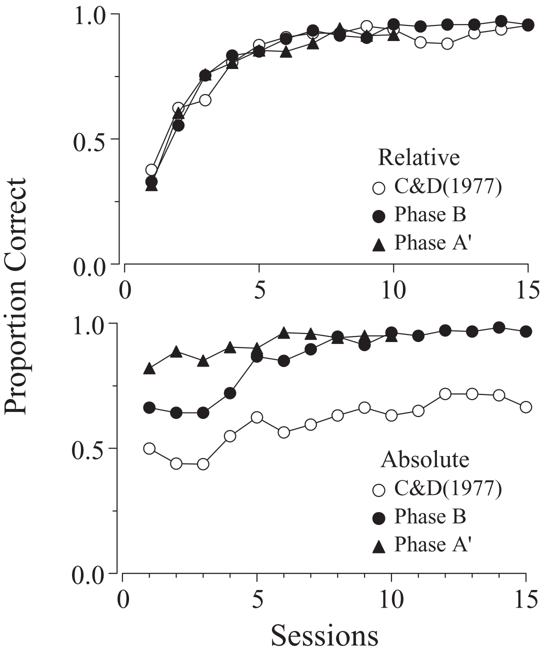

Fig. 9. Top. Average proportion of correct responses following the 4-s samples for the Relative group. The three data sets correspond to the rat data from Church & Deluty's (1977) study, and the pigeon data from the present study during Phases B and A′. Bottom. Corresponding data for the Absolute group.

group Relative will be more severe than the disruption following the 16-s or 1-s samples in group Absolute (in Figures 2 and 3, compare the first filled symbol of each curve in the top panels with the first empty symbol of each curve in the bottom panels). The data supported this prediction: Averaged across the first session of phase B and the first session of phase A′, the proportion of correct choices following the common sample equaled .32 for group Relative, whereas the proportion of correct choices following the new sample (1 s or 16 s) equaled .48 for group Absolute, $t(14) = 2.52$, $p = .025$. In fact, the model's predictions for the first session of phase B and the first session of phase A′ (see Figure 7, left panels) correlate strongly ($r = .84$) with the data (Figure 7, right panels).

Upshift versus Downshift groups. The data also revealed a few differences between the Upshift and Downshift groups. These differences are important because they show that performance does not depend exclusively on the ratio between the two sample durations. Although this ratio remained constant for all groups and phases, the magnitude of the disruptions during phase transitions varied. If the ratio of sample durations determines their discriminability, then we conclude that performance in general and the disruptions in particular depend on more than discriminability.

The largest differences between the Upshift and Downshift groups occurred during Phase B and they involved the common 4-s sample. The LeT model cannot account for these differences because LeT predicts equally severe disruptions for the Upshift and Downshift Relative groups and no significant disruptions for the Upshift and Downshift Absolute groups. With respect to the other samples, according to LeT the differences between the Upshift and Downshift groups stem from the degree of overlap of the three generalization gradients. Training the '1s→Left; 4s→Right' mapping during phase A, for example, will have only a weak effect on the tendency to peck Right following 16-s samples because the gradient centered at 4 s does not extend appreciably to 16 s. Hence, performance during the first session with 16-s samples should be close to chance (see also Siegel, 1986). In contrast, training the '4s→Left; 16s→Right' mapping during phase A will have a strong effect on the tendency to peck Left following 1-s samples because the gradient centered at 4 s extends appreciably to 1 s; hence performance during the first session with 1-s samples should be above chance.

Revisiting Church and Deluty (1977). Figure 9 compares our results with those reported by Church and Deluty (1977). For group Relative, the three curves overlap, showing that rats and pigeons behaved similarly. The average curves had the typical negatively accelerated exponential shape. But for group Absolute the curves do not overlap, for the pigeon curves are systematically above the rat curve. Interestingly, however, the curve from Phase B has roughly the same shape as the rat curve, concave up during the first sessions and concave down during the last sessions.

The results from the Absolute groups raise two interrelated questions. First, why were the acquisition curves from Phase B concave up initially? And second, why did accuracy following the common sample decrease in the Upshift group if the animals continued to receive food for choosing the same key as in the previous phase? The concave up initial segment may have resulted from the fact that, during the first sessions of Phase B, 2 pigeons showed negative covariations between the two discriminated operants (see Figure 8, pigeons P876 and P795). When proportion correct following the new sample increased, proportion correct following the common sample decreased.

We do not know whether these negative covariations occurred in Church and Deluty's (1977) study and what their causes might be. One possibility is that the extinction periods that necessarily occur during phase transitions reduce temporarily the control exerted by the conditional stimulus and strengthen positional biases. Consider the data from P795 in Figure 8. During the first session of Phase B, pigeon P795 preferred the Right key following the 4-s samples (83 % of correct choices) and was indifferent between the two keys following the 16-s samples (53 % of correct choices). Presumably because Right key choices following the 16-s samples were not reinforced, the pigeon started to choose the Left key following these longer samples and receive more rewards for pecking that key. It seems that, at that moment, location gained control over responding and, regardless of sample duration, choices became increasingly biased toward the Left key. This positional bias was revealed by the worsening of performance following the 4-s samples (47 % correct choices in session 2) concomitant with the improvement of performance following the 16-s samples (80 % correct choices by session 7). But then the effect of extinction of Left choices following the 16-s samples may have had its effect and performance fell to chance in sessions 3 and 4; finally, temporal control by sample duration gradually increased. We have observed similar negative covariations in naïve pigeons when first exposed to a bisection task. Clearly, the dynamics of the process remain to be worked out, but they are beyond the scope of the LeT model.

Concerning the disruption of performance following the 4-s sample, the challenge is to explain why it happened in the Upshift group but not in the Downshift group in phase B. The difference between the two groups seems incompatible with both the Absolute and the Relational Hypothesis because neither can explain in a principled way why performance following the common sample should be disrupted severely when the other sample is longer than the common sample (group Upshift) but not when it is shorter (group Downshift). We suggest a new account. In group Absolute Upshift, the new 16-s sample may have functioned as an extinction trial for the 4-s common sample because a longer interval necessarily includes a shorter interval (see also Russell & Kirkpatrick, 2007, Experiment 1, for a similar idea). If the first 4 s of the 16-s sample function like an extinction trial for the common sample, then performance following the common sample should approach indifference. In contrast, in group Absolute Downshift the new 1-s sample would not function as an extinction trial for the common 4-s sample and therefore performance following the common sample should remain accurate. The account becomes more plausible if one considers that the pigeons may have acquired distinct behavioral patterns during the sample (Machado & Keen, 1999). For example, during phase A the pigeons from group Absolute Upshift may have started the trials by approaching the key associated with the 1-s sample, stayed near that key and then, when the sample continued, moved to the key associated with the 4-s sample. During the first session of phase B, the pigeons from this group would have stayed near the key associated with the 4-s sample during most of the new 16-s sample, perhaps pecked that key at the end of the sample (stimulus generalization) and received no reinforcement. If the interval spent near the key associated with the 4-s sample was functionally similar to an extinction period, proportion correct following the common sample would have decreased, as it did. The foregoing account remains speculative but it can be tested by recording the pigeon's behavior during the sample (e.g., Machado & Keen) or by defining the comparison stimuli by key color instead of location. If the account is correct, in the latter case the disruptions should not differ between the Upshift and Downshift Absolute groups.

The present study does not support Church and Deluty's (1977) conclusion that a new bisection task is learned faster when it preserves the relational rather than the absolute mapping of the previous task. In fact, the results are more complex because each bisection task consists of two samples and therefore statements about the learning speed for on sample may not hold for the other sample. In addition, the effects on the new bisection task seem to depend on whether the previous task used longer or shorter sample durations. When the various acquisition curves are taken into account (i.e., Relative and Absolute, Upshift and Downshift), the data seem closer to the Absolute than the Relational Hypothesis.

To conclude, we do not claim that rats and pigeons can learn only about the absolute durations of stimuli. In fact, some studies have already shown that at least pigeons can respond relationally to two temporal intervals (e.g., Dreyfus, 1992; Fetterman & Dreyfus, 1986). But, in contrast with the bisection task, these studies involved explicit training of relational responding with multiple pairs of sample durations. We claim instead that there is no reliable evidence for relational learning in the temporal bisection task. More positively, most of our findings followed the pattern predicted by the LeT model, a simple instantiation of the Absolute Hypothesis. And though the model failed to account for a subset of the results, its overall goodness of (qualitative) fit suggests that, in the bisection task, temporal control is mostly absolute.

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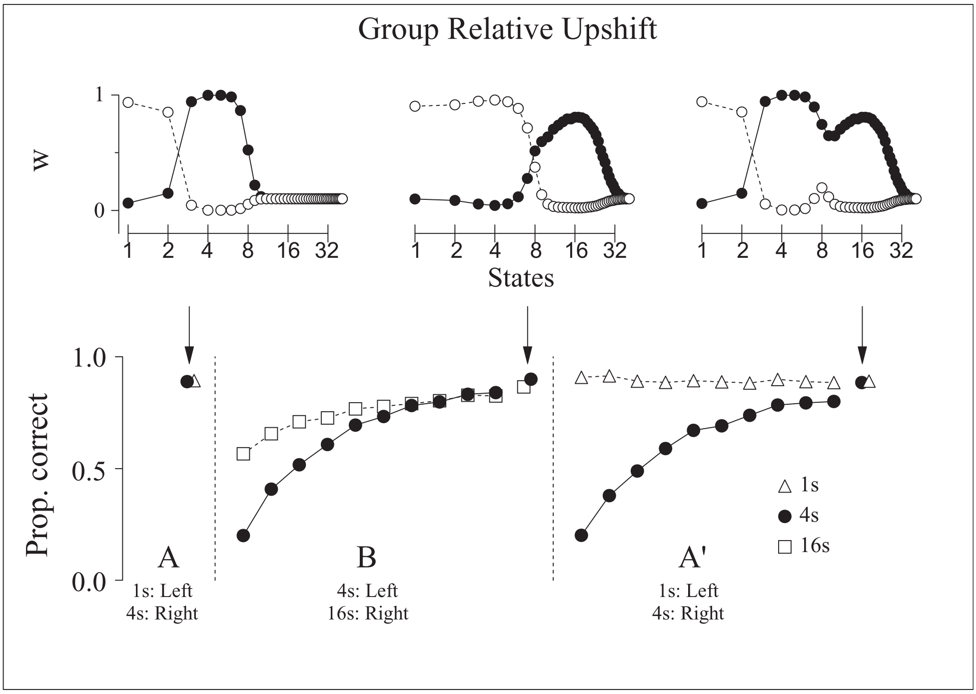

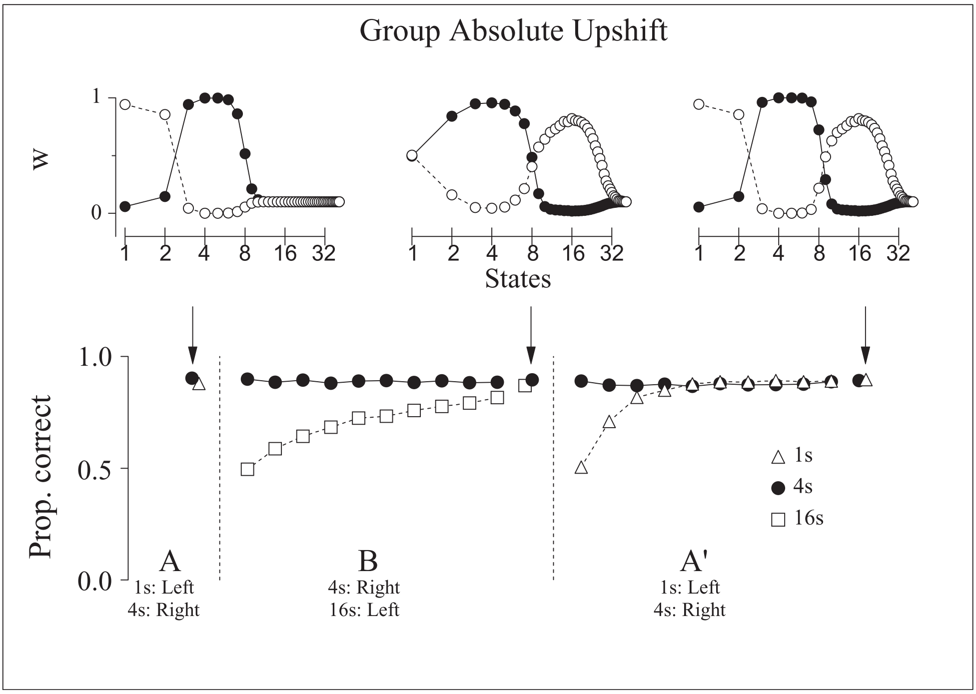

Fig. A1. Strength of the associative links and acquisition functions predicted by LeT for the Upshift groups. In each panel, the top row shows the strength of the associative links with the Left (empty circles) and Right (filled circles) responses at the end of Phases A, B, and A′. The bottom row shows, from left to right, the proportion of correct responses following each sample at the end of Phase A, during the first 10 and the last session of Phase B, and during the first 10 and the last session of Phase A′. The bottom panel shows the corresponding predictions for group Absolute. The arrows indicate that the associative links represented in the top rows correspond to the last session of each phase.

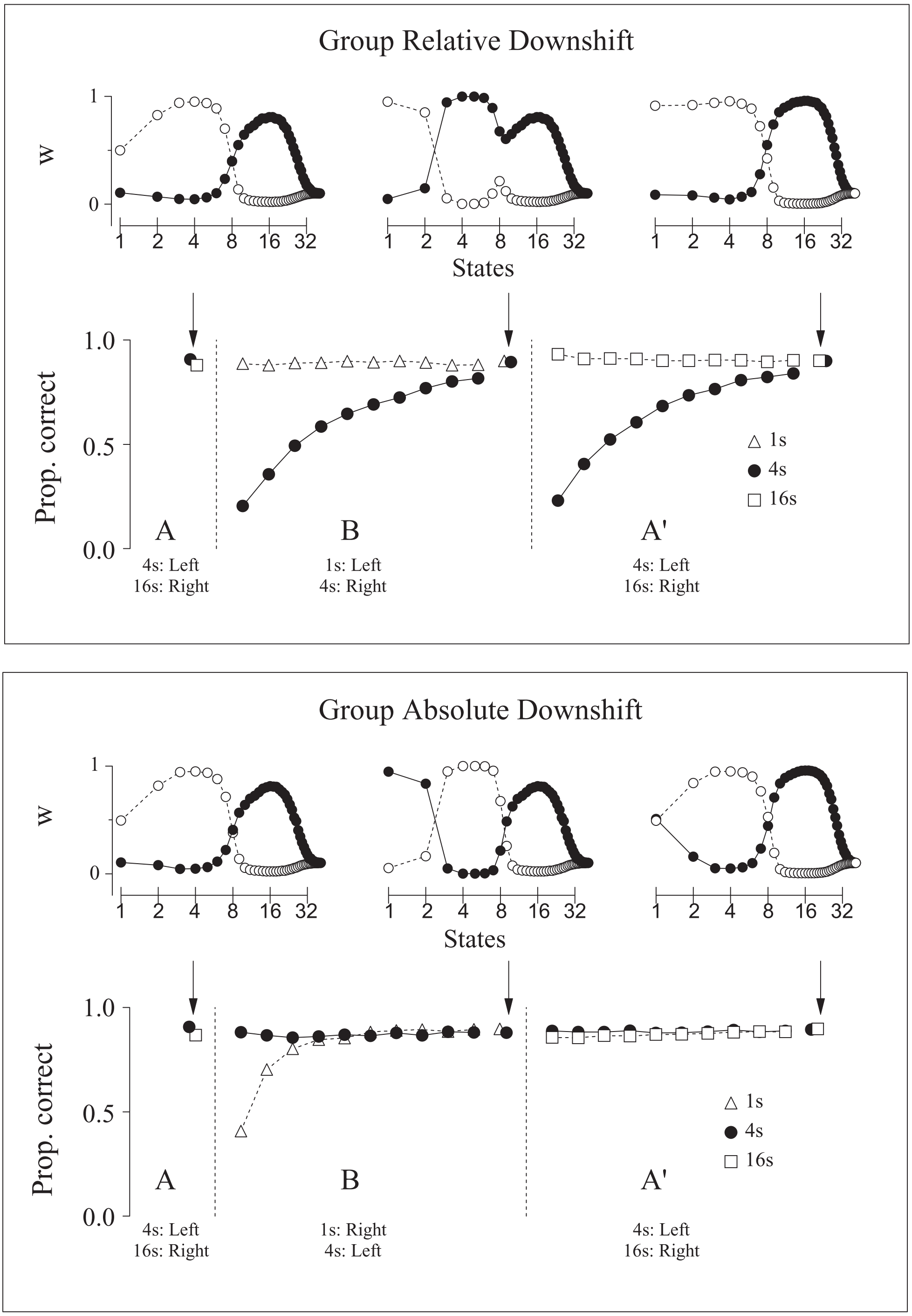

Fig. A2. Strength of the associative links and acquisition functions predicted by LeT for the Downshift groups. In each panel, the top row shows the strength of the associative links with the Left (empty circles) and Right (filled circles) responses at the end of Phases A, B, and A′. The bottom row shows, from left to right, the proportion of correct responses following each sample at the end of Phase A, during the first 10 and the last session of Phase B, and during the first 10 and the last session of Phase A′. The bottom panel shows the corresponding predictions for group Absolute. The arrows indicate that the associative links represented in the top rows correspond to the last session of each phase.

Table A1

Percentage of correct responses for each pigeon in the Relative Upshift and Relative Downshift groups in the first 10 sessions of phases B and A′.

		Relative Upshift								Relative Downshift							
		PG26		P572		P508		P068		P434		P454		P053		P665	
Ph.	Sess.	16 s	4 s	16 s	4 s	16 s	4 s	16 s	4 s	1 s	4 s	1 s	4 s	1 s	4 s	1 s	4 s
B	1	71.4	30.0	93.3	33.3	40.0	70.0	53.3	50.0	83.3	23.3	76.7	20.0	83.3	16.7	83.3	20.0
	2	86.7	20.0	76.7	93.3	50.0	76.7	96.7	56.7	66.7	73.3	83.3	56.7	73.3	53.3	80.0	13.3
	3	86.7	60.0	73.3	100.0	53.3	73.3	96.7	76.7	83.3	80.0	96.7	86.7	96.7	73.3	73.3	53.3
	4	66.7	70.0	86.7	100.0	76.7	83.3	96.7	83.3	83.3	83.3	96.7	90.0	96.7	66.7	83.3	90.0
	5	73.3	70.0	100.0	90.0	86.7	70.0	100.0	70.0	83.3	93.3	93.3	96.7	100.0	100.0	96.7	90.0
	6	66.7	80.0	93.3	93.3	93.3	86.7	100.0	76.7	96.7	96.7	90.0	86.7	100.0	100.0	86.7	100.0
	7	83.3	83.3	100.0	100.0	100.0	90.0	96.7	80.0	86.7	100.0	100.0	100.0	100.0	96.7	100.0	96.7
	8	73.3	80.0	100.0	100.0	100.0	96.7	93.3	70.0	86.7	100.0	86.7	90.0	93.3	93.3	96.7	100.0
	9	54.5	66.7	96.7	100.0	96.7	96.7	93.3	86.7	76.7	90.0	90.0	90.0	96.7	100.0	100.0	93.3
	10	83.3	90.0	93.3	100.0	96.7	100.0	93.3	86.7	86.7	100.0	96.7	93.3	100.0	100.0	93.3	96.7
		1 s	4 s	1 s	4 s	1 s	4 s	1 s	4 s	16 s	4 s	16 s	4 s	16 s	4 s	16 s	4 s
A′	1	83.3	36.7	96.7	3.3	96.7	40.0	90.0	26.7	100.0	40.0	83.3	33.3	76.7	33.3	100.0	40.0
	2	86.7	53.3	96.7	20.0	96.7	90.0	86.7	43.3	100.0	100.0	96.7	56.7	83.3	70.0	100.0	50.0
	3	93.3	73.3	86.7	40.0	96.7	96.7	86.7	60.0	93.3	100.0	93.3	56.7	93.3	90.0	100.0	90.0
	4	86.7	86.7	83.3	33.3	96.7	90.0	96.7	76.7	86.7	100.0	93.3	63.3	96.7	100.0	100.0	93.3
	5	80.0	83.3	80.0	60.0	96.7	96.7	80.0	73.3	100.0	96.7	100.0	83.3	100.0	93.3	100.0	96.7
	6	86.7	70.0	76.7	60.0	100.0	100.0	100.0	80.0	93.3	96.7	96.7	76.7	100.0	100.0	96.7	96.7
	7	80.0	50.0	93.3	90.0	96.7	96.7	83.3	83.3	100.0	93.3	86.7	96.7	100.0	100.0	90.0	96.7
	8	93.3	80.0	93.3	83.3	96.7	100.0	93.3	93.3	100.0	100.0	96.7	96.7	96.7	100.0	90.0	100.0
	9	96.7	83.3	96.7	83.3	100.0	100.0	90.0	80.0	93.3	100.0	100.0	93.3	100.0	93.3	96.7	96.7
	10	96.7	93.3	93.3	93.3	100.0	100.0	96.7	66.7	100.0	96.7	90.0	96.7	100.0	90.0	93.3	96.7

Table A2

Percentage of correct responses for each pigeon in the Absolute Upshift and Absolute Downshift groups in the first 10 sessions of phases B and A′.

		Absolute Upshift								Absolute Downshift							
		P876		P435		P236		P795		P093		P877		P784		P816	
Ph.	Sess.	16 s	4 s	16 s	4 s	16 s	4 s	16 s	4 s	1 s	4 s	1 s	4 s	1 s	4 s	1 s	4 s
B	1	40.0	53.3	40.0	33.3	50.0	36.7	53.3	83.3	23.3	93.3	20.0	90.0	10.0	66.7	53.3	73.3
	2	76.7	26.7	43.3	53.3	80.0	56.7	80.0	46.7	50.0	76.7	13.3	93.3	53.3	90.0	76.7	70.0
	3	80.0	66.7	46.7	53.3	73.3	50.0	43.3	56.7	90.0	93.3	63.3	36.7	73.3	73.3	50.0	83.3
	4	86.7	73.3	46.7	46.7	80.0	66.7	73.3	50.0	73.3	90.0	90.0	66.7	73.3	86.7	73.3	96.7
	5	93.3	96.7	80.0	80.0	70.0	80.0	90.0	90.0	93.3	100.0	93.3	83.3	66.7	76.7	93.3	86.7
	6	96.7	70.0	93.3	80.0	70.0	90.0	90.0	90.0	80.0	93.3	93.3	76.7	70.0	96.7	100.0	83.3
	7	86.7	86.7	100.0	90.0	80.0	86.7	80.0	80.0	96.7	93.3	90.0	93.3	86.7	96.7	90.0	90.0
	8	86.7	93.3	93.3	93.3	93.3	86.7	100.0	96.7	90.0	100.0	100.0	86.7	100.0	100.0	86.7	100.0
	9	93.3	96.7	86.7	83.3	96.7	86.7	100.0	96.7	86.7	100.0	96.7	80.0	90.0	93.3	96.7	93.3
	10	100.0	90.0	93.3	100.0	90.0	96.7	93.3	100.0	90.0	100.0	96.7	90.0	96.7	96.7	96.7	96.7
		1 s	4 s	1 s	4 s	1 s	4 s	1 s	4 s	16 s	4 s	16 s	4 s	16 s	4 s	16 s	4 s
A′	1	53.3	90.0	56.7	93.3	43.3	53.3	50.0	100.0	56.7	63.3	30.0	90.0	93.3	90.0	100.0	76.7
	2	70.0	83.3	96.7	96.7	53.3	56.7	60.0	96.7	93.3	100.0	93.3	90.0	96.7	93.3	96.7	93.3
	3	90.0	70.0	100.0	86.7	70.0	83.3	80.0	86.7	96.7	90.0	96.7	86.7	96.7	93.3	96.7	83.3
	4	90.0	66.7	96.7	96.7	80.0	93.3	80.0	96.7	96.7	90.0	96.7	86.7	93.3	96.7	100.0	96.7
	5	70.0	83.3	96.7	76.7	80.0	86.7	73.3	96.7	83.3	96.7	90.0	93.3	100.0	96.7	100.0	90.0
	6	93.3	86.7	100.0	93.3	86.7	93.3	96.7	100.0	100.0	100.0	66.7	100.0	100.0	100.0	96.7	96.7
	7	83.3	100.0	100.0	96.7	83.3	96.7	93.3	93.3	96.7	100.0	66.7	90.0	100.0	96.7	100.0	93.3
	8	90.0	100.0	100.0	93.3	90.0	86.7	90.0	93.3	96.7	100.0	83.3	93.3	100.0	100.0	100.0	86.7
	9	100.0	100.0	96.7	100.0	93.3	90.0	96.7	93.3	100.0	96.7	90.0	90.0	100.0	96.7	100.0	93.3
	10	90.0	96.7	100.0	100.0	93.3	90.0	100.0	86.7	100.0	100.0	100.0	90.0	100.0	100.0	100.0	96.7