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Context effect in a temporal bisection task with the choice keys available during the sample

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ABSTRACT

In a symbolic matching to sample task, six pigeons learned to associate different sample durations with different comparison stimuli. On "Short" trials, choice of Red and Green keylight comparisons were reinforced following 3-s and 9-s samples, respectively; on "Long" trials, Blue and Yellow keylight comparisons were reinforced following 9-s and 27-s samples, respectively. In contrast with previous studies, the comparison keys were available during the samples. After the temporal discriminations were learned, new pairs of comparison keys were presented and the preference for each was assessed during 27-s samples. One pair in particular, Green and Blue, was critical because it tested the predictions of two timing models, Scalar Expectancy Theory (SET) and the Learning-to-Time (LeT) model. The results showed that preference for Green increased during the sample, a result consistent with LeT but not with SET. Other test results, however, were predicted by neither model.

1. Introduction

Throughout the last decades, our understanding of how animals time events has increased significantly. Researchers have developed a variety of procedures to explore, among other issues, the accuracy of temporal regulations, the discriminability of different intervals of time, or the distortions of time perception (e.g., Gallistel, 1990; Richelle and Lejeune, 1980; Shettleworth, 1998). To account for the results obtained with these procedures, quantitative models have been developed and tested. The present study continues a series of experiments (Arantes and Machado, 2008; Machado and Arantes, 2006; Machado and Keen, 1999; Machado and Pata, 2005; Oliveira and Machado, 2008) designed to contrast two of these models, Scalar Expectancy Theory or SET (Gibbon, 1977, 1981, 1991) and the Learning-to-Time or LeT model (Machado, 1997; Machado and Cevik, 1998).

The experiments used a double temporal bisection task, which is a combination of two simple temporal bisection tasks. In a simple temporal bisection task (e.g., Church and Deluty, 1977) a subject learns to associate two sample durations with two comparison stimuli. To illustrate (see Fig. 1), suppose a pigeon is presented with a white light for 1 s or 4 s and then two choice keys are lit with Red and Green lights. Choices of Red and Green are reinforced after the 1-s and 4-s samples, respectively. We call these trials "Short" trials. After the pigeon learns this discrimination, another simple bisection task is introduced, but with a different pair of sample durations, 4 s and 16 s, and a different pair of comparison keys, Blue and Yellow. Choices of Blue and Yellow are reinforced after the 4-s and 16-s samples, respectively. We call these trials "Long" trials. After the pigeon learns the second discrimination, the Short and Long trials are presented within the same session – hence, a *double* temporal bisection task.

The additional complexity introduced by the double bisection task is justified by the fact that the simple bisection task does not differentiate the two models of timing. Consider the typical stimulus generalization test used in simple bisection tasks. After learning to choose the Red and Green keys following 1-s and 4-s samples, respectively, a pigeon is presented with intermediate sample durations and its preference for, say, the Red key, is assessed. The psychometric function relating the probability of choosing Red to sample duration has two key properties (see, e.g., Catania, 1970; Church and Deluty, 1977; Fetterman and Killeen, 1991; Platt and Davis, 1983; Stubbs, 1968). First, the point of subjective equality (PSE) is close to the geometric mean (i.e., $\sqrt{(1 \times 4)}$) of the two training durations. Second, the psychometric functions obtained with different pairs of training durations with the same ratio (e.g., 1-s vs. 4-s samples in the first discrimination, and 4-s vs. 16-s samples in the second discrimination, such that 1/4 = 4/16) superimpose when plotted in relative time. Unfortunately for model comparison, both SET and LeT predict these properties of the psychometric function (Gibbon, 1981, 1991; Machado, 1997).

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The double bisection task enables the experimenter to run more sensitive tests. In addition to the stimulus generalization test described above, the experimenter can also run stimulus–response generalization tests in which new pairs of keylights are presented following samples of different durations. Returning to the example in Fig. 1, the test that gives the pigeon a choice between Green and Blue following samples that vary from 1 s to 16 s is critical because it differentiates clearly the SET and LeT models. Fig. 2 shows the predictions of each model. Whereas SET (top left panel) predicts that the pigeon will be indifferent between Green and Blue regardless of sample duration, LeT (top right panel) predicts that the pigeon's preference for Green will increase monotonically with the signal duration.

To understand these predictions, consider the structure of each model. SET (bottom left panel; for mathematical details see Gibbon, 1981, 1991) postulates a pacemaker that emits pulses at a high and variable rate. These pulses are added in an accumulator for the duration of the sample. If, after the sample, the subject is reinforced for choosing, say, the Red key, then the pulses in the accumulator are transferred to a memory store associated with the Red key. According to SET there is a different memory store associated with each reinforced comparison (in this case, with each of the four keylight colors). In addition, the contents of each memory store represent the duration of the sample associated with the reinforced comparison. Hence, in the double bisection task, the four stores, which we label "Red", "Green", "Blue", and "Yellow", will represent the durations of 1 s, 4 s, 4 s, and 16 s, respectively. To decide which key to choose, say, Red or Green, after a stimulus with duration *T*, the animal compares the number of pulses in the accumulator at the end of the stimulus, X_T, with a sample retrieved from the Red store, X_{Red}, and a sample retrieved from the Green store, X_{Green}.

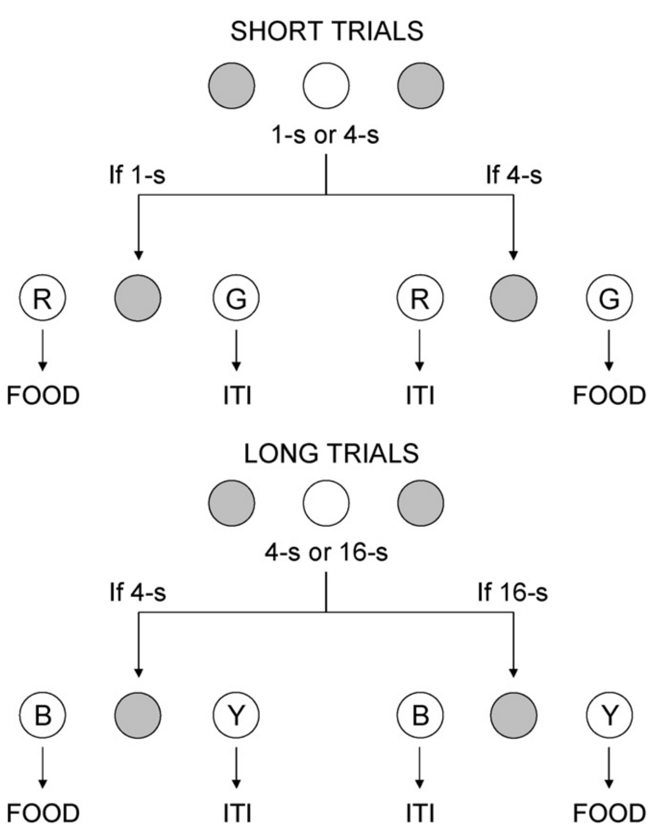

Fig. 1. Structure of the two types of training trials on a double bisection task. On Short trials, samples of 1 s or 4 s are associated with Red (R) or Green (G) comparison stimuli, respectively. On Long trials, samples of 4 s or 16 s are associated with Blue (B) or Yellow (Y) comparison stimuli, respectively.

If $X_T/X_{\text{Red}} < X_{\text{Green}}/X_T$ the animal will choose Red, otherwise it will choose Green.

In SET, the contents of a memory store depend only on the corresponding sample. The Green and Blue stores, for instance, will both represent 4-s durations regardless of the fact that the two comparison stimuli occur in different contexts (i.e., whereas the context for Green is the 1-s sample associated with Red, the context for Blue is the 16-s sample associated with Yellow). It follows that the Green and Blue memory stores will be statistically identical and for that reason the comparison between any test duration and samples extracted from the Green and Blue stores will yield, on the average, indifference between the two keys. To summarize, because in SET the temporal representations are context independent, the model predicts no effect of sample duration on the preference for Green over Blue.

LeT (bottom right panel; for mathematical details see Machado, 1997; Machado and Pata, 2005) assumes a series of behavioral states that are linked with the instrumental responses. The states become active in succession during the sample. We refer to the behavioral states active at the end of 1-s samples as the initial states, the ones active at the end of 4-s samples as the middle states, and the ones active at the end of 16-s samples as the final states. The strength of the associative links, equal at the onset of training, will vary with the reinforcement contingencies. For example, because the 1-s samples are associated with Red, the links between the initial states and Red will become strong through reinforcement, whereas the links between these states and Green will become weak through extinction. The opposite will be true for the middle states (i.e., their association will be strong with Green and weak with Red). The same reasoning applies to the Long trials, but in this case Blue will become strongly associated with the middle states and weakly associated with the final states, whereas Yellow will become strongly associated with the final states and weakly associated with the middle ones. Notice that LeT is not context independent because the strength of the links will reflect the specific contingencies of the discrimination task (i.e., which choices are reinforced and extinguished after which specific sample durations). Therefore, given a choice between Green and Blue, after 1-s samples the initial states are the most active and because their association with Green is weak, the pigeon will avoid Green and choose Blue; after 16-s samples the final states are the most active and because their association with Blue is weak, the pigeon will avoid Blue and choose Green; after 4-s samples the middle states are the most active and since their association with both Green and Blue is equally strong, the pigeons are indifferent between the two colors. More generally, LeT predicts that preference for Green over Blue will increase with the sample duration.

This context effect (i.e., preference for Green over Blue increases with sample duration, even though Green and Blue were associated with the same 4-s samples) has been obtained using different kinds of tests (Machado and Arantes, 2006; Machado and Keen, 1999; Machado and Pata, 2005) and versions of the double bisection procedure (Arantes and Machado, 2008; Oliveira and Machado, 2008). The effect provides strong support for LeT and casts serious doubt on SET's account of temporal discrimination.

In the present study, our aim was to check the generality and robustness of the context effect using a new version of the bisection task. Following Platt and Davis (1983; see also Stubbs, 1976), we made the two choice keys available from the beginning of the sample. Returning to the example above, instead of illuminating the sample key with white light and then, at the end of sample, presenting the two choice keys, we lit the two choice keys and then apply the same reinforcement contingencies after the sample duration elapses. That is, after the sample duration is over, the first peck is reinforced only if it is at the correct key. We predicted that, instead of engaging in idiosyncratic behaviors during the sam-

ple (see Machado and Keen, 1999; Arantes and Machado, 2008), the pigeons would peck the choice keys, perhaps even following a specific pattern: on Short trials, start pecking the Red key and then, if the trial continues, switch to the Green key; similarly, on Long trials, start pecking the Blue key and then, if the trial continues, switch to the Yellow key (Machado and Keen, 2003). In the present study we asked whether the context effect would be preserved when the pigeon pecks during the sample.

Although we have stressed the Green vs. Blue stimulus–response generalization test, three other tests are possible, Red vs. Yellow, Green vs. Yellow, and Red vs. Blue. Fig. 2 (top panels) shows the predictions of both models for these new pairs of comparison stimuli. In the Red vs. Yellow test, both models predict a monotonically decreasing curve. For the Green vs. Yellow and Red vs. Blue tests, SET predicts curves that are scale transforms of the Red vs. Yellow curve. On the other hand, LeT predicts a U-shaped curve for the Red vs. Blue test and an inverted U-shaped curve for the Green vs. Yellow test. Previous studies (Machado and Keen, 1999; Machado and Pata, 2005) have supported LeT's predictions. Therefore, in the present study we asked whether those predictions remain adequate when the choice keys are available during the sample stimulus.

The final purpose of the study was to determine whether the results mentioned above would be obtained with a different ratio between the two pairs of sample durations. Instead of the 4:1 ratio used in previous studies, in the present experiment we used a 3:1 ratio, associating Red with 3 s, Green and Blue with 9 s, and Yellow with 27 s.

2. Method

2.1. Subjects

Six pigeons (*Columba livia*) were used in the experiment. All subjects had previous experience with a concurrent timing task. The pigeons were maintained at 80% of their *ad lib* weight. Water and grit were continuously available in their home cages, and a 14:10 h light/dark cycle (lights on at 7:00 a.m.) was in effect in the pigeon colony.

2.2. Apparatus

Three identical LehighValley® experimental chambers for pigeons were used. The front panel of each chamber contained three keys centered on the wall, 2.5 cm in diameter, 8 cm apart center to center, and 22 cm above the wire mesh floor. The side keys could be illuminated from behind with red, green, blue, or yellow light, and the center key could be illuminated with white light. A 6 cm × 5 cm hopper opening centered on the wall directly below the center key gave access to mixed grain when it was raised and illuminated with a 7.5-W white light. Another 7.5-W white light, situated on the back wall of the chamber, provided general illumination. Each intelligent panel was enclosed by an external box equipped with a fan to provide ventilation and mask extraneous noises. Three personal computers programmed in C++ controlled the experimental events and recorded the data.

2.3. Procedure

The experiment was divided into three phases: training, pretesting, and testing. In the training phase, the pigeons learned the two basic discriminations; in the pre-testing phase, sessions included Short and Long trials, but some of these trials were in extinction; the testing phase included the stimulus–response generalization tests.

2.3.1. Training

After a single autoshaping session, the birds learned one of the two basic discriminations, Short (i.e., 3 s vs. 9 s) or Long (i.e., 9 s

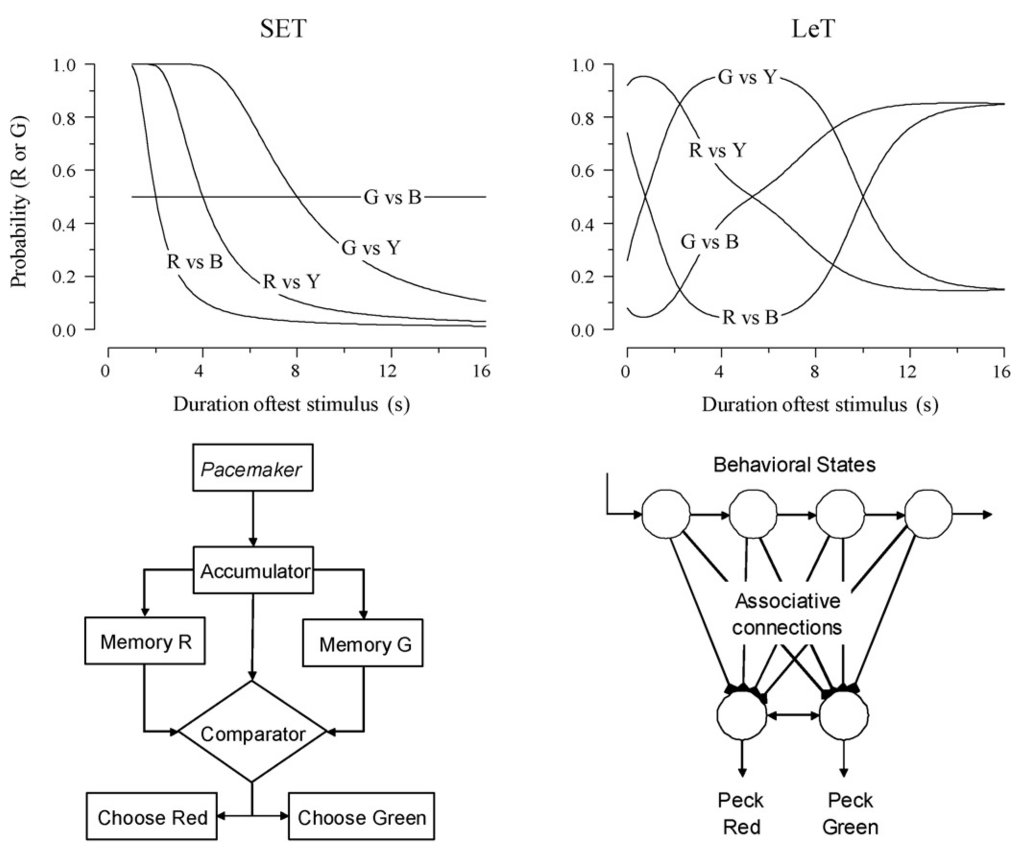

Fig. 2. Predictions for the stimulus–response generalization tests (top) and structure (bottom) of the Scalar Expectancy Theory (left) and the Learning-to-Time (right) models.

vs. 27 s), with their order counterbalanced across birds. There were two assignments of keylight colors to sample durations and each assignment was used for half of the birds: (a) Short trials, 3 s → Red, 9 s → Green, and Long trials, 9 s → Blue, 27 s → Yellow; and (b) Short trials, 3 s → Yellow, 9 s → Blue, and Long trials, 9 s → Green, 27 s → Red. However, for clarity, the procedure and the experimental results are described as though all birds had the first assignment above. The two keylight colors presented during Short or Long trials always appeared the same number of times on the left and right keys. In addition, within each set of Short or Long trials, the number of trials with the short sample always equaled the number of trials with the long sample.

Sessions comprised 64 trials, each of which had the following sequence of events: the houselight and the center key were illuminated with white light. A peck on the center key turned the center key off and illuminated the side keys with the choice colors (e.g., red and green). The peck was required to make sure that the pigeon saw the onset of the comparison stimuli. After the sample duration elapsed (e.g., 3 s), the first peck at any of the choice keys turned all keylights and the houselight off. If the choice was correct, the hopper was activated from 2 to 4 s, according to the pigeon – reinforcement duration was adjusted to maintain body weight and minimize post-session feedings. After the reinforcer, a 45-s ITI followed. If the choice was incorrect, the ITI followed immediately and the trial was repeated (correction method). If the bird made three consecutive errors, only the correct key remained illuminated after the sample duration, essentially "forcing" the pigeon to peck it and collect the reinforcer.

On the Long trials, most pigeons stopped pecking the white center key or had extremely long latencies. To solve this problem, the peck on the center key was reinforced with food with a probability that decreased during training until it reached the value of 0.05. This value remained in effect for the remainder of the experiment.

Once the birds learned the first discrimination (i.e., at least 80% correct choices, excluding repeated trials, for five consecutive sessions), they were exposed to the second discrimination. After the second discrimination was learned, the two types of trials, Short and Long, alternated across sessions until performance stabilized. This training phase lasted from 21 to 30 sessions (mean = 26).

2.3.2. Pre-testing

In this phase, each session comprised 32 Short and 32 Long trials. In each set of 32, 16 were for the shortest and 16 were for the longest sample durations. During the first five to eight sessions (mean = 6.2), correct choices were reinforced and incorrect choices repeated the trial. These trials are called "regular trials". In the next seven to nine sessions (mean = 7.5), extinction trials replaced some regular trials to adapt the pigeons to the lower reinforcement rate in effect during the test sessions. The number of extinction trials increased from 8 to 16 to 24. Besides not ending with food, extinction trials were not repeated. The stability criterion remained the same, at least 80% correct choices over five sessions for each of the four sample durations.

2.3.3. Testing

This phase lasted for four sessions, each comprising 40 regular trials (20 Short and 20 Long) and 24 stimulus–response generalization test trials. During the test trials, after the pigeons pecked the white center key, new pairs of choice keys appeared. Each of the four sessions tested the pigeons' preferences with a different pair of choice keys. The order of the tests was Green vs. Blue, Red vs. Yellow, Red vs. Blue, and Green vs. Yellow. The duration of the test trials was always 27 s and they ended without a reward. The two choice colors appeared the same number of times on the left and right keys. Finally, to reduce the effects of testing on the two basic discriminations, after each test session the pigeons received three sessions with regular and extinction trials only (as in the pre-testing phase).

3. Results

The pigeons needed 26 sessions on average to learn the 2 basic discriminations. In the last five sessions of the pre-testing phase, the overall proportion of correct responses ranged from 0.94 to 0.98 (average = 0.96), and from 0.81 to 1.0 across the four signal durations.

As anticipated, the availability of the choice keys during the trial promoted the following behavior in all subjects: When the choice keys were illuminated, the pigeons started to peck the key associated with the shortest duration (Red on the Short trials, Blue on the Long trials); they continued to peck that key until either the trial ended with reinforcement or an interval of time between the two training durations (i.e., between 3 s and 9 s on Short trials and between 9 s and 27 s on Long trials) had elapsed, whichever occurred first. If the latter, then the pigeons switched to the other choice key, associated with the longer duration, and pecked it until the end of the trial. This pattern accounted for 81% of all trials (range across pigeons: 73–91%). On the remaining trials, the pigeons switched keys at least twice, did not peck one of the keys, or pecked the keys in the opposite order (e.g., the pigeon started to peck the key associated with the longest duration). We excluded these "anomalous" trials from the analysis.

Given the time of the last peck at the first key (t_1) and the time of the first peck at the second key (t_2), we estimated the moment of switching on each trial, $t_S = (t_1 + t_2)/2$. From the distribution of the t_S values, we computed the probability of switching as a function of time into the trial.

Fig. 3 displays the average probability that a pigeon was still pecking the Red or Blue keys as a function of trial duration. The sample durations on the Long trials were divided by three so that both curves could be compared directly. The results show a clear superimposition of the two curves, which decreased monotonically with stimulus duration and had PSEs close to 5.5 s, slightly above the geometric mean of the training durations (5.2).

In the testing phase, the pigeon's behavior in the presence of the new key pairs was more variable than in the presence of the training key pairs. Therefore, on test trials, preference could not be measured by the moment of switching and had to be measured by relative response rate. Fig. 4 displays the average results for all four tests. Consider the critical test, Green vs. Blue. Except for the first

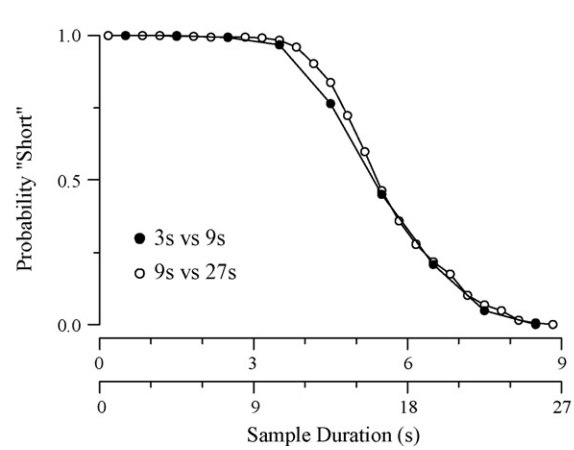

Fig. 3. Probability of choosing Red on the Short trials and Blue on the Long trials as a function of sample duration. The durations on the Long trials were divided by 3 so that the curves could be directly compared.

2 s, the curve reproduces the context effect, that is, preference for Green tends to increase with sample duration. The context effect is consistent with LeT but not with SET. The discrepant data from the first 2 s must be interpreted with caution because overall response rate was significantly lower during that period than during subsequent periods. Hence, preference during the initial segment of the curve may be unreliable.

The curve for the Red–Yellow test shows that preference for Red decreased with sample duration, an effect predicted by both models. The curve for the Green–Yellow test shows that preference for Green increased initially and then decreased almost linearly until the end of the trial. However, for the reason mentioned above, the initial segment of the curve may be unreliable. The result from this test is not consistent with either model because both models predict a strong preference for Green at 9 s, the duration associated with Green. Finally, the curve for the Red–Blue test shows that preference for Red remained strong for the first 6 s, decreased to 0.1 at 15 s, and then increased slightly until the end of the sample. This result is only partly consistent with each model because, on the one hand, SET does not predict the late increase in preference for Red and, on the other hand, LeT does not predict such strong preference for Red during the first seconds and it predicts too strong an increase in that preference at the end of the sample (see Fig. 2).

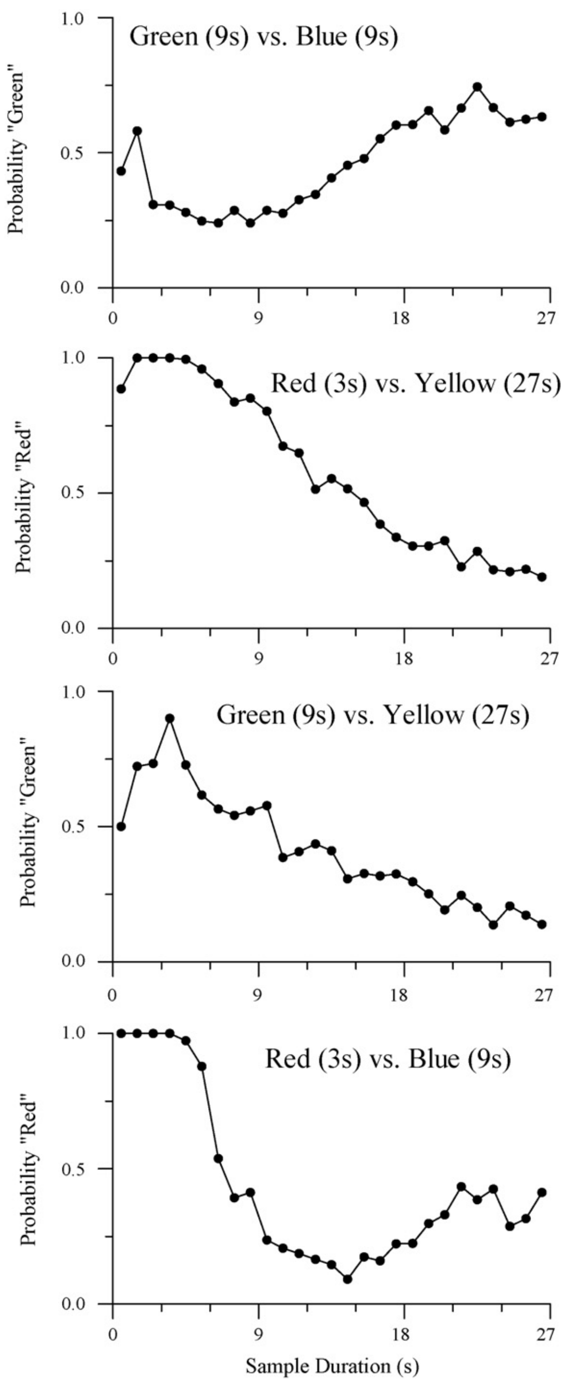

Fig. 4. Average results for the four new key pairs in the stimulus–response generalization tests. Each panel shows the probability of choosing Red or Green as a function of sample duration.

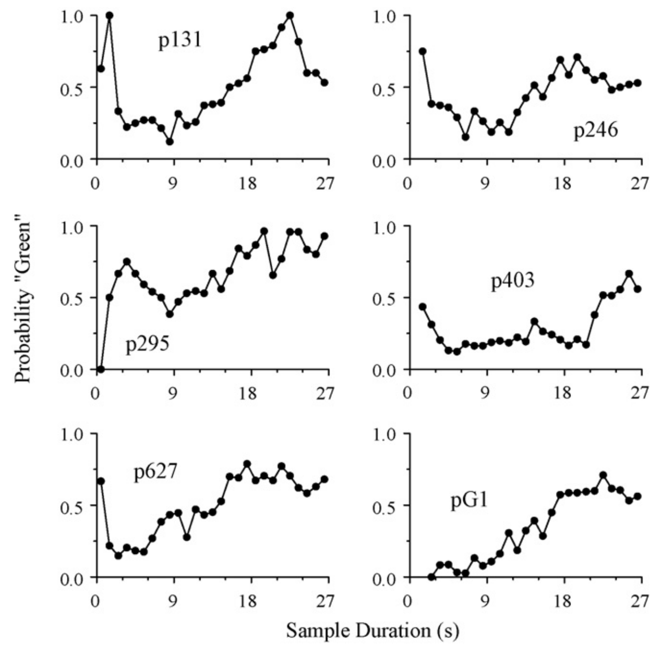

Fig. 5. Individual results for the stimulus–response generalization test between the Green and Blue keys. The probability of choosing the Green key is plotted against the sample duration.

Individual differences were more pronounced in the Green–Yellow and Red–Blue tests than in the Red–Yellow and Green–Blue tests. Because the Green-Blue test is theoretically the most important, Fig. 5 shows the individual results. Despite differences in the PSEs (e.g., P403 and P295), it is clear that, after the first 1 or 2 seconds, preference for Green tends to increase with sample duration – the context effect.

4. Discussion

This study extended Platt and Davis (1983) version of the bisection task to a double bisection procedure. Pigeons learned to associate four different colors, presented in two pairs, to three sample durations. However, unlike in previous studies, the choice keys were available throughout the samples.

All pigeons learned the double bisection task. Moreover, they seemed to learn it considerably faster than when the choice keys were unavailable until the end of the sample. In fact, whereas in the present study the pigeons needed 26 sessions on average to learn the task, in previous studies, with the choice keys unavailable until the end of the sample, they needed from 31 to 43 sessions on average to learn an *easier* task (the task was easier in previous studies because the sample durations were in a 1–4 ratio whereas in the present study they were in a 1–3 ratio).

One way of explaining why learning was faster in the present study is as follows. When the choice keys are unavailable, most pigeons develop stereotypical behaviors during the sample (e.g., Machado and Arantes, 2006; Machado and Keen, 1999). These behaviors may provide additional cues that facilitate the temporal discrimination (Fetterman et al., 1998; for a discussion of mediating behaviors, see Richelle and Lejeune, 1980; Staddon and Ayres, 1975; Staddon and Simmelhag, 1971). When the choice keys are available during the sample, the pigeons do not need to develop stereotypical behaviors because they may simply peck the keys. Not only does pecking behavior emerge faster, it may also provide better additional cues (perhaps related to total number of pecks) that facilitate the temporal discrimination.

When the choice keys were available during the sample, the pigeon's typical behavior consisted in pecking the key associated with the shorter duration and then switching to the key associated with the longer duration. From the distribution of the switching points it was possible to assess the preferences for the two keys during the sample. The results showed that preference for the key associated with the shorter duration lasted until approximately the geometric mean of the two training durations. In addition, the preference curves on the Short and Long trials superimposed when plotted on a common axis, a clear demonstration of the scalar property. Although not shown, an alternative analysis based on relative response rate instead of the distribution of switching times yielded the same findings, almost complete superimposition of the two curves and PSEs at the corresponding geometric means. These results are consistent with the results obtained in previous studies with the double bisection procedure (e.g., Machado and Keen, 1999; Oliveira and Machado, 2008). They are also consistent with the predictions made by both the LeT and SET models.

In the stimulus–response generalization tests, four new color combinations were presented in 27-s trials. Behavior during the sample was more variable than during the previous phases, but preference could still be measured by relative response rate. The results from the critical test between the Green and Blue keys showed that preference for the Green key tended to increase with sample duration – the context effect. With two exceptions, the preference function obtained with the choice keys available during the sample was similar to the preference function obtained with the choice keys unavailable. The exceptions were (a) the stronger preference for Green during the first 2 s of the sample and (b) the higher PSE when the choice keys were available (according to previous studies, the PSE should have been close to 9 s, the duration associated with the Green and Blue keys, and not to 15 s). The first exception may be unreliable because the number of responses during the first 2 s was very low. We discuss the second exception below.

The preference function from the Red–Yellow tests also reproduced the function obtained in previous studies except that, again, the PSE was located around 15 s, significantly above 9 s, the geometric mean of durations associated with Red (3 s) and Yellow (27 s). With respect to the preference functions from the Green–Yellow and Red–Blue tests, their trends were somewhat similar to the ones obtained in previous experiments (Machado and Keen, 1999; Machado and Pata, 2005) in the sense that preference for Green over Yellow and for Red over Blue generally decreased with sample duration. However, the exact shapes of the functions differed, particular at the shortest and longest sample durations. Specifically, the function for Green–Yellow showed a weaker preference for Green at 9 s than when the keys were unavailable and the function for Red–Blue showed a stronger initial but a weaker final preference for Red than when the keys were unavailable. In contrast with the Green–Blue and Red–Yellow tests, the Green–Yellow and Red–Blue tests yielded more individual differences between the preference functions. These differences preclude any stronger conclusions.

We mentioned above that the PSE for the Green–Blue test (≈15 s) was greater than when the keys were unavailable during the sample. One post hoc account of this result could be that the pigeons did during the test trial what they had learned to do during the training trials, namely, to switch away from Blue around 15.6 s, the geometric mean of 9 s (Blue) and 27 s (Yellow). But this account means that while pecking the Blue key during the test trials, the color of the alternative key did not affect the moment of switching. This account is incompatible with the PSE obtained in the Red–Yellow tests. In fact, if the pigeons had done during the test trials what they had learned to do during the training trials, namely, to switch away from Red around 5.2 s, the geometric mean of 3 s (Red) and 9 s (Green), the account would predict a PSE of 5.2 s during the Red–Yellow tests, whereas the obtained value was close to 15 s.

Alternatively, one could think that the second key controlled the moment of switching. Because during training the pigeons learned to switch to Yellow at approximately 15 s, they switched at 15 s during the Red–Yellow test trials. Unfortunately, the same account would predict a PSE at 5.2 s in the Blue–Green tests. In summary, neither account can explain the PSEs of the Green–Blue and Red–Yellow preference functions. The issue remains to be explained.

In conclusion, the present results show that (a) pigeons can learn a double temporal bisection task in which the comparison stimuli are presented during the sample; (b) having learned the task, the pigeons reproduce the context effect on stimulus–response generalization tests, the effect predicted by LeT, but not by SET; however, (c) several features of the data including the shape and PSE of the preference functions and the substantial variability among subjects on some generalization tests remains to be explained.

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