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What is learned during simultaneous temporal acquisition? An individual-trials analysis

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Abstract

The processes involved in the acquisition of simultaneous temporal processing are currently less understood. For example, it is unclear whether scalar property emerges early during simultaneous temporal acquisition. Using an information-processing model which accounts for the amount of information that each temporal process provides in regard to reward time, we predicted that scalar property would emerge early during the acquisition process, but that subjects should take about 27% longer (more trials) to acquire the long duration than the short duration. To evaluate these predictions, we performed individual-trials analyses to identify changes in timing behavior when rats simultaneously acquire two criterion durations, either 10s and 20s (group 10/20) or 20s and 40s (group 20/40). To analyze the individual trials we used a change-point algorithm to identify changes in rats' wait time. For each individual rat, and for each criterion duration, analyses indicated that simultaneous temporal acquisition is characterized by a sudden change in waiting to a wait-time proportional to the associated criterion. The results failed to indicate group differences in regard to the number of trials it takes for the change in wait-time to occur, but that in both groups, it took longer (more trials) to acquire the long duration than the shorter one, not significantly different from the theoretical prediction. These results are discussed in the framework of an information-processing model informing both associative and temporal learning, thus providing a bridge between the two fields.

Introduction

There has been a considerable effort to build theories to describe both associative (Rescorla and Wagner, 1972; Mackintosh, 1975; Pearce and Hall, 1980; Buhusi and Schmajuk, 1996, Buhusi et al., 1998) and temporal learning (Machado, 1997; Buhusi and Schmajuk, 1999; Gibbon, 1977, 1991; Church et al., 1994; Killeen and Fetterman, 1988; Staddon and Higa, 1999). In these associative and temporal learning theories, there is an underlying hypothesis that learning is a gradual, continuous process toward an asymptotic performance, updated upon every trial. As a consequence, the usual procedure to investigate the speed of learning is to define a parameter that measures the level of performance, measuring the number of

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trials for which the group average reaches this level (Fry et al., 1960; Church et al., 1991; Caetano et al., 2007).

A different perspective has been proposed by Gallistel and colleagues (Gallistel et al. 2001a, 2004a, b). In this perspective the learning (or at least its behavioral expression) is an abrupt, sharp process with no asymptotic performance (Gallistel et al., 2009). Also, the smooth asymptotic behavior would be an artifact of group averaging, possibly hiding important information about individual processes (Estes and Maddox, 2005). Alternatively, a method usually referred as change point analysis was proposed to be more accurate for the individual description of the behavior, looking for points of abrupt changes (Gallistel et al., 2001a, 2004a,b, 2009). There is a current debate about the smooth versus abrupt change in behavior (see for example Nevin, 2012; Gallistel, 2012). However, regardless of the actual nature of learning, change point analysis can provide us with an interesting tool for analyzing speed of learning on individual level, avoiding possible problems created by averaging across animals.

The change point algorithm (Gallistel et al. 2004a,b) has been previously used to analyze the acquisition in interval timing tasks (Papachristos and Gallistel, 2006; Balci et al., 2009). The analysis consists of finding transitions between low and high response rates within individual trials (start and stop points, Church, Meck and Gibbon, 1984), and looking for discontinuous changes in these quantities over trials. Abrupt changes in behavior have been reported both in associative (Gallistel et al. 2004a) and temporal learning paradigms (Gallistel et al. 2004b) (Papachristos and Gallistel, 2006; Balci et al., 2009). The findings seem to be consistent across experiments, and across species (King et al, 2001b, Gallistel et al, 2004b), revealing abrupt changes in behavior and no asymptotic performance.

Here we examine acquisition of simultaneous temporal processing. Currently, it is unclear whether scalar property emerges early during simultaneous temporal acquisition. On one hand, irrespective of the method used to analyze performance in timing tasks, one expects that average performance after a number of trials should be consistent with the Scalar Expectancy Theory (SET) (Gibbon 1977). For a fixed-interval (FI) procedure, this means that after a certain number of trials, the start time should be proportional to the criterion (Church et al., 1994; Balci et al., 2009; Catania 1970). On the other hand, SET is a steady-state model, which does not describe the acquisition process, such that the question on whether scalar property emerges early or not in a simultaneous temporal processing procedure is currently unanswered.

Moreover, the processes involved in learning two pairs of stimulus-interval associations simultaneously (simultaneous temporal processing) are also unclear. Would the animals present an abrupt change in start time for each of the intervals independently, similarly as when they learn these intervals separately? If so, would the start times be proportional to the intervals right after the change point, or the animals would delay a fixed amount of time for both trials before a further improvement in performance? Would the change points happen at the same point in the session for both intervals, or the subjects would first learn one duration before the other?

To address these questions, we first derived a theoretical prediction relative to the speed of learning two durations in our experimental setting: Briefly, during simultaneous acquisition of two intervals, I_S (short) and I_L (long), with I_L is twice as long as I_S , subjects are expected to take about 30% more trials to learn the long intervals. Second, we tested this prediction in two groups of rats trained to simultaneously acquire either 10s/20s criteria, or 20s/40s criteria. This theoretical prediction was confirmed experimentally.

Study 1: Theoretical analysis

The purpose of this study was to derive a theoretical prediction of the regarding the speed of learning in two groups of rats trained simultaneously with two criterion intervals (10s/20s or 20s/40s), in a discrete-trials paradigm with inter-trial intervals (ITIs) about 3 times longer than the criteria. The speed of learning is assumed to be proportional to the information conveyed by the stimuli: should the signal for one interval (say, the short one) convey more information than the other one (indexed by the ratio of their entropies), then one would predict that the subjects would learn the first interval faster than the second.

Methods

According to (Ward et al., 2013; Balsam and Gallistel, 2009), both during associative and temporal learning, subjects' performance is guided by the information conveyed by the CSs regarding the reinforcement. In timing protocols, this information is the difference between the entropy of the distribution of the inter-reinforcement intervals (time between USs) and the entropy of the inter-reinforcement intervals given that the CS is present. In contrast to cue-competition protocols, here we assumed that there was no competition between the two cues signaling the two criterion durations (conditioned stimuli, CSs), since they were never present at the same time and they represented two different intervals (FI short and FI long). In our protocol, the ITI for both trial types was identical (cue lights off), except that the ITIs lasted for a duration that was 3 times longer (on average) than the FI trial (that has just been presented). Since the trials were randomized and the ITIs were identical (cue lights off), the ITIs did not convey information about when the next US was to be presented. Taking this into consideration, we assumed that the ITIs from both trial types were just part of a single distribution. This should distort the proportionality between the average ITI and the criterion for the short and long FI trials. This can be better seen in the entropy calculation below.

Following the same line of reasoning presented in (Balsam and Gallistel, 2009; Ward et al. 2013), the information conveyed increases with the ratio between the US-US interval (I_{us}) and the CS-US interval (I_{cs}), I_{us}/I_{cs} , and has an extra increment related to the logarithm of Weber fraction (w) and a constant value. Therefore, the conveyed information H can be written as follows:

$$H = \log_2 \frac{I_{us}}{I_{cs}} - \log w + \frac{1}{2} \log_2 \frac{e}{2\pi}, \quad \text{Eq. (1)}$$

where w is the Weber fraction. The last term contains only constants and is approximately -0.60 bits. Using the generally accepted value for the Weber fraction (Balsam and Gallistel,

2009), $w=0.15$ the middle term is about 2.74 bits. Eq (1) should hold for all FI trials, both short and long.

Therefore, during simultaneous temporal acquisition, the difference between the information conveyed by the two trial types (criterion durations) resides on the I_{cs} value. In our setting, in both groups of rats, the duration of the CS-US interval in the short trials (I_S) is half than for the long trials (I_L), i.e., $I_S = I_L/2$. Hence, the entropies for short FI trials, H^S and long FI trials, H^L become

$$\begin{aligned} H^S &= \log_2 \frac{I_{us}}{I_S} + 2.14 \\ H^L &= \log_2 \frac{I_{us}}{I_L} + 2.14 \end{aligned} \quad \text{Eq. (2)}$$

Moreover, in our setting, the ITI was on average 3 times the duration of the criterion duration. Therefore, the duration of an average trial can be estimated by the average time of the CS plus the ITI. Lumping all the trial durations for the short ($I_S + 3I_S$) and for the long ($2I_S + 6I_S$) trial types, we have an average US-US interval equal to $6I_S$. Including that on Eq. (2):

$$\begin{aligned} H^S &= \log_2 \frac{6I_S}{I_S} + 2.14, \text{ and} \\ H^L &= \log_2 \frac{6I_S}{2I_S} + 2.14, \end{aligned} \quad \text{Eq (3)}$$

yielding 4.72 and 3.16 for the short and long entropies, respectively. The ratio of these entropies is 1.27, suggesting that in our setting the short stimulus would convey 27% more (bits of) information about reinforcement time than the long stimulus.

Results

Since entropy was proposed to be inversely related to the number of trials to acquisition (Gallistel et al., 2004), our analysis indicates that during simultaneous acquisition of two intervals, I_S (short) and I_L (long), with I_L is twice as long as I_S , the short interval conveys 27% more information about the reinforcement than the long interval. Under the supplemental assumption of a linear (first order approximation) relationship between the inverse of the number of trials and entropy, our analysis predicts that it would take 27% more trials to acquire the long criterion relative to the short criterion. Finally, our analysis suggests that the above result should hold irrespective of intervals, as long as I_L is twice as long as I_S .

Study 2: Experimental evaluation

We evaluated these predictions by analyzing the change points in start times for rats trained to simultaneously time two different FI intervals (10s/20s for group 10/20, and 20s/40s for group 20/40). Because our theoretical analysis suggests that the above result should hold irrespective of intervals as long as I_L is twice as long as I_S , and because in our setting the

ratios I_S / I_L , and I_{US} / I_{CS} were equal in the two groups, our analysis predicts that both groups should acquire the short duration about 27% faster than the long duration, with no group differences. To evaluate these predictions, for all subjects, and for each FI trial type, we identified the start times in trials just after the first change point in behavior. These start times were contrasted by trial type (short vs. long) and by group (10/20 v. 20/40), to check for differences in wait times at the time of the first change point. Interestingly the start times were not only different for short and long trials, but they showed a striking proportionality with the timed interval. Finally, we tested the prediction that the change points occurs 27% later for long and short FI trials, in both groups.

Methods

Subjects—The subjects were 16 three month-old naive male Sprague-Dawley rats (Charles River, Wilmington, USA) weighting between 200 and 250g at the beginning of the experiment. Animals were housed in groups of two in a 12h light/dark cycle with the light being turned on at 7am and off at 7pm. All procedures were conducted during the light cycle. Subjects were randomly assigned to two groups: Group 10/20 was trained simultaneously in FI 10s and FI 20s procedures and Group 20/40 was trained simultaneously in FI 20s and FI 40s procedures. Animals were handled according to the Institutional Animal Care & Use Committee of the Medical University of South Carolina.

Apparatus—Animals were trained in 8 matching operant boxes ENV-007 (Med Associates, Inc., Model ENV-007) within a sound- and light- attenuating cubicles equipped with an exhausting fan. The top and the door of the operant boxes were made of clear acrylic plastic. The walls were aluminum and the floor consisted of parallel of stainless steel rods. Each box was equipped with two levers located on each side of the magazine with two cue lights about 7 cm above each lever, and a house light on top of the back wall (opposed to the food magazine).

Timing procedure—Rats were shaped to lever press during two daily sessions of fixed ratio, during which they received a maximum of 64 food pellets. In the next day, the rats were trained with a dual Fixed Interval (FI) procedure, as follows. Each trial started when one of the cue lights (left or right, counterbalanced) was turned on. The first lever press after the criterion associated with the cue light turned it off and was reinforced with a food pellet. The cue lights were associated with short and long criteria, counterbalanced. Trials were separated by random inter-trial intervals (ITIs), ranging from 2.5 to 3.5 times the criterion associated with the current trial, uniformly distributed. Both levers were permanently available for pressing. Sessions ended when rats received 64 trials of each type (Short or Long). Data from the first 4 daily dual FI sessions, gathered in a single dataset were submitted for analyses, as follows.

Start time estimates—Trials were separated by type: short (10s for group 10/20 and 20s for group 20/40) or long (20s for group 10/20 and 40s for group 20/40) and analyzed separately. Start times were calculated as follows: For each trial, the response rate (in 100ms bins) was convolved with a Gaussian kernel with a 2s standard deviation. The start time was defined as the point where the convolved function reached half of its maximum. As in

Church et al. (1994), trials where the start time exceeded the criterion were excluded from the analysis (to avoid using trials when the animal took long breaks).

Change point analysis—For each rat, and for each trial type (short or long), the start times were submitted to the change point algorithm developed by Gallistel et al. (2004). In short, the procedure builds a cumulative function C of the start point values as a function of the trials (T), ranging from the initial (T_i) and final (T_f) trial. A tentative change point was determined as the point of the cumulative function C that deviated the most from the straight line connecting $[T_i, C(T_i)]$ and $[T_f, C(T_f)]$. The start points were then separated in two conditions, 20 trials before and 20 trials after the tentative change point (trial) and the two distributions were compared using a t test, at a defined significance level ($logit$). If the start times in the two conditions (trials before and trials after) were significantly different at the given significance level, trial T_i was designated as an actual change point. The analysis was repeated for the start points before and after the change point, until no more change points were found. For the results shown here, we tested different $logit$ levels of significance, $L=3.0, 3.5, 4$, and 4.5 , and averaged the results over L values for each individual and condition.

For illustrative purposes, panels A and B of Figure 1 show data from the first 150 trials of two subjects, one in group 10/20 (panel A) and one in group 20/40 (panel B), in the form of a raster plot (bottom left graph in each panel). Each raster plot shows all the responses made (small black dots), as a function of time (x axis) and trial (y axis). The data were divided in two by a red line, which shows the location where a change in behavior was detected (change point). The start times before (blue) and after the change point (orange) were shown as larger dots for each trial. Graphs above the raster plots show the distribution (histograms) of starts before and after the change point, in the same color as the colored dots in the raster plots.

In order to identify whether there was a detectable abrupt difference in behavior we made “local” comparisons, which consisted in comparing the distributions of start times before and after each trial, using a t -test. For example, for trial 30, the start times from trials 11 to 30 and from the trials 31 to 40 were compared. The statistical comparison provides a p -value of rejecting the null hypothesis (no difference between the distributions). With the p -value, we calculate the associated odds $(1-p)/p$ of rejecting the null hypothesis. Repeating that for all the trials between 21 and 130, we obtained the graph shown on the right of the raster plots. Regions where there are high odds correspond to low p -values, and consequently trials where the 20-trial windows before and after were significantly different. Notice that each graph reveals one main, isolated, very sharp peak, which was also represented in the raster plots by the red dash line. The sharpness of the highest peak and the absence of peaks of similar amplitude suggest that there is a singular, abrupt change in behavior at the change point.

However, in accord with reports by other investigators (e.g., Harris 2011), for some rats we failed to find change points within the first 4 sessions for at least one of the trial types. These subjects were not included in the analyses; as such, 2 rats in group 10/20 and 2 rats in group 20/40 were eliminated from analyses (group 10/20 $n=6$; group 20/40 $n=6$). Although for

these rats we failed to identify change points, possibly indicative of failure to acquire the temporal aspects of the task in the first four sessions, these rats were clearly able to differentiate the trials from the inter-trial intervals. Their rates of response during the trial, 26.9 responses/min, dropped during the inter-trial interval to 3.6 responses/min, with an average suppression ratio of 0.13 ± 0.02 .

The start time after the first detected change point and the trial where it occurred were submitted to repeated measures ANOVAs with group (10/20 v. 20/40) as a between-subjects variable, and trial (short v. long) as a within-subjects variable, with an alpha level of 0.05.

Results

It is known that start times are proportional to the criterion when subjects are trained in a single FI schedule (Church et al., 1994). Therefore, in the current study we investigate whether in a dual-FI paradigm start times were proportional to the criterion interval after the change point, i.e., whether for both FI trials, the waiting behavior changes in one single “jump” to a start time proportional to the criterion. Alternatively, animals could simply start responding after the same amount of time for both FI trials.

Figure 2 shows the average start times after the first change point, by trial type and group. A repeated measures ANOVA with group (10/20 v. 20/40) as a between-subjects variable, and trial type (short v. long) as a within-subjects variable, indicated a significant main effect of group ($F(1,10)=219.95$, $p<10^{-6}$), and trial type ($F(1,10)=21.34$, $p<0.001$), but no group $\times$ trial interaction ($F(1,10)=0.16$, $p>0.69$). These results indicate that the longer the criterion, the larger the start time. A post-hoc (Fisher LSD) analysis indicated reliable differences between the short and long trials in both the 10/20 ($p<0.02$) and 20/40 groups ($p<0.01$).

To test whether start times were proportional to the criterion of each trial type, we performed a similar analysis on the start times in percent criterion. This analysis indicated a reliable effect of trial type ($F(1, 10) = 8.66$, $p<0.02$), but no effect of group ($F(1, 10)=0.11$, $p>0.75$) or group $\times$ trial interaction ($F(1, 10)=0.14$, $p>0.72$), suggesting that the start times were proportional between groups, but that the proportionality was disrupted within group.

To further test this hypothesis, we plotted the start times as a function of the criterion (Figure 3a). This graph showed a clear proportionality between the start time and criterion ($r=0.89$, $p=10^{-4}$). Finally, when results were plotted in proportional time (Figure 3b), the correlation vanished ($r = -0.34$, $p>0.10$), supporting the hypothesis that start times were proportional to the criterion. It is interesting to note that post-hoc comparisons in proportional time indicated a difference between the start times for the FI20 trials in the two groups (Fisher LSD test, $p<0.04$), even though these trials had equal criteria durations. This result suggests that mixing the FI trials had an influence on the start times, probably creating a different temporal context for both trial types (Buhusi & Meck, 2009).

Next we turned our attention to the question of whether the acquisition of two fixed intervals happened within the same number of trials. For each group and trial type we determined the trial when the change occurred, the change trial (CT). A repeated-measures ANOVA of the CT with group (10/20 v. 20/40) as a between-subjects variable, and trial type (short v. long)

as a within-subjects variable, indicated a significant main effect of trial type ($F(1,10)=15.27$, $p<0.01$), but no main effect of group ($F(1,10)=4.54$, $p>0.05$) or interactions ($F(1,10)=15.27$, $p<0.01$), indicating that CT is larger in the long trial relative to short trials, in accord with our theoretical prediction.

However, as can be seen in figure 4, the distributions seem to depart from normality. This observation was supported by analyses of skewness and kurtosis, which departed from being unitary. For both groups, skewness was smaller than 0.54 for short trials, and smaller than 0.82 for long trials. Also, kurtosis was larger than 1.38 for short trials, and larger than 1.52 for long trials. Therefore, we performed non-parametric comparisons between change trials in short and long trials. For both groups, at an alpha-level of 0.05, a two-tailed Wilcoxon test indicated a reliable difference between short and long trials ($W(6)=19$, $p<0.05$), thus, thus confirming that in both groups it took more trials to change behavior when learning the long criterion than for the short criterion.

Overall, the average number of trials to change point was 42.4 ± 2.2 for short trials, and 72.1 ± 8.0 for long trials, not reliably different than the $42.42 * 1.27 = 53.87$ trials predicted theoretically, $t(11)=2.14$, $p>0.05$. Even though these statistics *per se* cannot prove that the model is correct, the results do show that there is a difference between the number of trials to acquire the task for short and long trials, and no difference when all durations are increased proportionally (no difference between groups), which are exactly the non-trivial predictions of the model.

Discussion

The question of whether learning is a smooth or an abrupt process is matter of current debate. The question is particularly difficult because of the high level of noise observed in the data, as shown in Figure 1. A systematic investigation on the subject was made by (Papachristos and Gallistel, 2006). Here, we brought a different perspective, by calculating the level of significance (odds) of a “local” comparison and plotting it throughout the trials (Figure 1). Although our results do not unarguably show that the acquisition is all or nothing, for at least some of our subjects (75%), there seemed to be a single change point with orders of magnitude more significance (odds) than elsewhere in the sessions.

Although inspired by the change point algorithm proposed by (Gallistel et al., 2004), the method used here (presented in Figure 1) differs from it. First, because it compares always two groups of n adjacent trials, the number of samples is kept constant for all the comparisons, allowing for a global comparison of odds of change throughout the sessions. Second, this method may be used to rank change points (in case there are more than one candidate) before having to divide the dataset in sub-groups for further analyses. Finally, our method does not assume *a priori* that the changes are abrupt; this conclusion comes as a consequence of the graph interpretation. Further investigation about this method is required to identify its strong and weak points compared to other methods.

The results shown here suggest that, even when the trials are mixed, the start times are close to proportional to the trial criterion right after the first detectable change point, for both trial

types (Figure 2). If animals were trained in a single FI schedule, it would not be surprising that the performance after the detected change point were proportional to the trial criterion, since it is known that the performance in FI trials follow the scalar property (Church et al., 1994). What is surprising in this case is that it happens independently and for both trial types, for the same subject. This suggests that for each trial type, the subjects produce one important change point (trial), after which, in subsequent trials, they wait an amount of time proportional to the criterion. Predicting this particular effect would have been difficult, because most of the timing theories (Machado, 1997; Buhusi and Schmajuk, 1999; Gibbon, 1977, 1991; Church et al., 1994; Killeen and Fetterman, 1988; Staddon and Higa, 1999) predict the timing of the responses, but use update rules upon reinforcement that predict a continuous, smooth change in behavior. On the other hand, Gallistel and colleagues (e.g., Balsam and Gallistel, 2009) predict an abrupt change in behavior, but does not predict the timing of the change. So, at this point, from a theoretical point of view, it is not clear how to reconcile these two views.

Interestingly, the start times after the change point (in proportional time units) were different in the two groups during the FI20s trials, despite the fact that the cue lights were counterbalanced, and the criterion intervals and the duration of the ITI following the reinforcement were identical. The only difference between the two groups was that these trials were mixed with another FI task: FI10s for group 10/20 or with FI40s for group 20/40. Apparently, this dissimilarity was enough to produce a significant difference between subjects' performances, suggesting that the temporal context can bias the performance on start times. Similar effects have been reported by Jazayeri and Shadlen (2010) in experiments with humans, where time estimates were different depending on the distribution from which they were drawn.

Another effect observed in our experiment was that the number of trials to acquisition for each trial type was different, but that no differences were observed between groups. If the trials were analyzed separately (as it was the case here), they would look identical to single FI tasks. In other words, most timing theories would predict the same learning curve for all trial types, which is inconsistent with our experimental results. The effect of mixing trials has a clear effect (as mentioned above) creating a temporal context and modulating behavior. Interesting, using Gallistel's informativeness theory (Gallistel et al., 2004; Balsam, 2009), we were able to predict the ratio between the number of trials to acquisition between the long and short trials. In our Study 1, we showed that the theory predicts that, if the relationship between the durations of the trial and the ITI were kept equal for both groups, there should be no difference between groups in the number of trials to acquisition. This prediction was confirmed experimentally in Study 2.

These results support Gallistel's suggestion (Gallistel et al., 2004) that both associative and temporal learning follow similar rules, based on informativeness of cues (Balsam et al. 2009). Evidence for abrupt changes in behavior has been reported both in associative (Gallistel et al. 2004a) and temporal learning paradigms (Gallistel et al. 2004b; Papachristos and Gallistel, 2006; Balci et al., 2009), both in birds (Gallistel et al. 2004), rats (Gallistel et al. 2001a), and mice (King et al, 2001b, Gallistel et al, 2004b), suggesting that information processing may be the missing link between the associative and temporal learning fields.

The question of information processing is of particular interest for neurobiological investigations (see Durstewitz et al., 2010 for example). Taken together, future investigations should evaluate what other relationships between parameters of learning (e.g., number of trials to change) can be extracted at a theoretical point of view, and tested experimentally. The current studies provided evidence that some relationships can be predicted and tested experimentally, to further test the hypothesis that behavior is driven not by contingencies but by informativeness, both in the associative and temporal domains.

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Start-time change trial and odds

Figure 1.

Examples of FI trials during a session for two subjects, one (A) from group 10/20, short trials (FI10s) and another (B) from Group 20/40, long trials (FI40s). For each figure, the raster plot (left, below) represents the animal responses (black dots) over time for each trial. The blue and orange dots represent the start (wait) times on each trial, and the vertical black line denotes the criterion. Notice that the behavior seems to present two distinct phases, one for trials before a change point (red and green lines) and the other after it. The green line shows the position of the change point obtained by Gallistel's algorithm, while the red line shows the change point obtained with the method of "local" changes described below. This difference in behavior before and after the change point can be observed also on the distribution of the start (wait) times, above each raster plot. On the right of the raster plots it is shown the odds ($((1-p)/p)$) of having a significant difference on the start times 20 trials before and 20 trials after a certain trial, as a function of the trial. This computes "local" changes in the distributions. The sharpness of the higher peak and the absence of peaks of similar amplitude suggest that there is one principal, abrupt change in behavior at the change point.

Figure 2.
Comparison by groups and trial type of the average start times ($\pm$ SEM) after the change point.

Individual Start time

Figure 3.

Start times as a function of the criterion. Group 10/20 is shown in triangles and group 20/40 in circles. Short trials are shown in blue while the long trials in red. Lines represent the data fit to the points. a) Start points correlate with the criterion, suggesting that after the first change point the subjects already show the scalar property. b) When displayed relative to the criterion, the correlation vanishes. Data points 20s from each group were slightly displaced horizontally to improve visualization, but the displacement was not used for data analysis.

Figure 4. Change points (trials where the first change point occurs), by group and trial type. The change trial occurred later for the long criterion than for the short criterion, irrespective of group.