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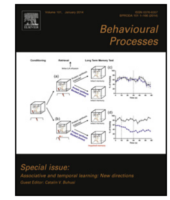

What is learned during simultaneous temporal acquisition? An individual-trials analysis

Marcelo Bussotti Reyes[a,*], Catalin V. Buhusi[a,b,**]

[a] Department of Neurosciences, Medical University of South Carolina, Charleston, SC, United States
[b] Department of Psychology, USTAR BioInnovations Center, Utah State University, Logan, UT, United States

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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 10 s and 20 s (group 10/20) or 20 s and 40 s (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.

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1. 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 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., 2001, 2004). In this perspective the learning (or at least its behavioral expression) is an abrupt, sharp process with no asymptotic performance (Gallistel et al., 2004). 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., 2001, 2004). 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., 2004) 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

* Corresponding author at: Universidade Federal do ABC, Rua Santa Adélia 166, Santo André - SP, CEP 09.210-170, Brazil.
** Corresponding author at: Utah State University, USTAR BioInnovations Center, 2810 Old Main Hill, Logan, UT 84322, United States.
E-mail addresses: marcelo.reyes@ufabc.edu.br (M.B. Reyes), catalin.buhusi@usu.edu (C.V. Buhusi).

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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., 2004) and temporal learning paradigms (Gallistel et al., 2004) (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., 2004), 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 10 s/20 s criteria, or 20 s/40 s criteria. This theoretical prediction was confirmed experimentally.

2. Study 1: Theoretical analysis

The purpose of this study was to derive a theoretical prediction regarding the speed of learning in two groups of rats trained simultaneously with two criterion intervals (10 s/20 s or 20 s/40 s), 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.

2.1. Methods

According to Ward et al. (2013) and Balsam and Gallistel (2009), both during associative and temporal learning, subjects' performance is guided by the information conveyed by the CS' regarding the reinforcement. In timing protocols, this information is the difference between the entropy of the distribution of the inter-reinforcement intervals (time between US's) 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, CS's), 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 looked identical (cue lights off), and lasted 3 times (on average) the FI trial that had just been presented. Since the trials were randomized and the ITIs looked 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 ITI's 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) and 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:

$$H = \log_2 \frac{I_{us}}{I_{cs}} - \log_2 w + \frac{1}{2}\log_2 \frac{e}{2\pi} \tag{1}$$

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.

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

$$H^S = \log_2 \frac{I_{us}}{I_s} + 2.14 \quad H^L = \log_2 \frac{I_{us}}{I_L} + 2.14 \tag{2}$$

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):

$$H^S = \log_2 \frac{6I_s}{I_s} + 2.14 \quad \text{and} \quad H^L = \log_2 \frac{6I_s}{2I_s} + 2.14 \tag{3}$$

yielding 4.72 and 3.16 bits 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.

2.2. 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.