



# Associative and temporal processes: A dual process approach



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## ABSTRACT

Approaches to the study of associative learning and interval timing have traditionally diverged on methodological and theoretical levels of analysis. However, more recent attempts have been made to explain one class of phenomena in terms of the other using various single-process approaches. In this paper we suggest that an interactive dual-process approach might more accurately reflect underlying behavioral and neural processes. We will argue that timing in Pavlovian conditioning is best understood in terms of an abstract temporal code that is not a feature of the predictive stimulus (i.e., the conditioned stimulus, CS), per se. Rather, we assume that the time between the CS and the unconditioned stimulus (US) is encoded in the form of an abstract representation of this temporal interval produced as an output of a central multiple-oscillator interval timing system. As such, associations can then develop between the CS and this abstract temporal code in much the same way that the CS develops associations with different features of the US. To support the dual-process approach, we first show that exposure to a Pavlovian zero contingency procedure results in a failure to acquire new associations, not a failure to express learning due to some temporally defined performance mask. We also consider evidence that supports the abstract temporal coding idea in a US preexposure task, and, finally, present some evidence to encourage the dissociation between basic associative and temporal learning processes by exploring reward devaluation effects in a peak timing task.

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## 1. Introduction

Theories of associative learning have become rather sophisticated in their treatment of simple forms of Pavlovian and instrumental learning in the last several decades. During this same time period theories of animal timing processes have also evolved in a number of interesting ways. It is a rather surprising fact that theories in these two domains have evolved largely independently of one another, though there are, of course, a large number of points of contact and, indeed, particular theories that have been proposed

to explore those points of contact. In spite of this, however, by our estimation, the main flavor of these theoretical advances has been to propose ways in which either, on the one hand, timing effects can be understood in essentially associative terms, or, on the other hand, associative effects can be understood in terms of basic timing mechanisms. It is almost as though members of each of these distinct communities do not wish to acknowledge the existential status of the type of explanatory mechanism employed by members of the other community.

A fundamental problem, therefore, is in determining whether the sorts of conditioned behaviors that we study and take to be the product of associative or timing processes are, in fact, reflective of a common set of underlying mechanisms or dissociable ones. In other words, do timing and associative effects come from the same underlying set of mechanisms or different ones?

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Let us clarify by considering a simple example. Suppose that a rat were to be trained in a Pavlovian learning task where a 30-s conditioned stimulus (CS) ended in the delivery of a food pellet unconditioned stimulus (US). Over the course of learning the rat will eventually come to respond by approaching the food magazine during the CS at levels that exceed pre-CS levels and that also exceed levels displayed in a random control group (e.g., [Delamater and Holland, 2008](#)). Moreover, when looking at responding at different moments in time over the 30-s CS period, one notices that the rate of magazine responding steadily increases as the time to the actual food delivery gets nearer. Note that this finding is commonly observed when averaging responding over blocks of trials, and we do not at this point wish to enter the debate as to whether or not responding is an all or none process. The main point here is that two clearly noticeable changes in the rat's behavior occur as a result of this training regimen – increased responding and temporally organized responding.

One common way of explaining results of this sort posits the existence of a basic associative learning process. The CS enters into an association with the US and this is responsible for producing increases in conditioned magazine approach responding. However, while this approach explains the increase in responding as reflecting a change in the associative status of the CS it requires additional assumptions if temporally organized responding is to be explained. The associative approach can readily accommodate this aspect of the data by assuming the existence of a series of “micro” stimuli or discriminable states initiated by the onset of the CS. If the CS elicits a cascade of temporally discriminable micro stimuli, and if it was assumed that there exists stimulus generalization among similar micro stimuli, then temporally organized responding can be explained quite efficiently. This tactic was probably first introduced by Pavlov in his discussion of inhibition of delay (1927, pp. 103–104) and, more recently, has been suggested in a number of different forms (e.g., [Buhusi and Schmajuk, 1999](#); [Killeen and Fetterman, 1988](#); [Ludvig et al., 2012](#); [Machado, 1997](#); [Staddon and Higa, 1999](#); [Vogel et al., 2003](#)) and has also been used to explain how cerebellar timing circuits work in the conditioned eyeblink paradigm (e.g., [Grossberg and Schmajuk, 1989](#); [Kehoe et al., 1993](#); [Medina et al., 2000](#)). Notice that this approach assumes that “timing” is regarded as something that occurs “within” the CS. There is no separate timer or timing process, per se, but, rather, temporally organized behavior reflects control by the particular CS-evoked discriminable process that is most strongly associated with the US.

In contrast, another way of characterizing the situation is to start with the assumption that the animal encodes the times at which critical events, like rewards, arrive. If the animal keeps a running record, for example, of how many times the pellet occurs and at what times, then the animal can base its “decision” to respond or not upon various computations performed on this record of the raw data. Early versions of this approach were introduced by Jenkins and his colleagues (e.g., [Jenkins et al., 1981](#)) and by [Gibbon and Balsam \(1981\)](#). According to Jenkins et al., the animal will respond when the “waiting time” to the US within the CS period is appreciably less than the waiting time to the US in the overall session. If the CS substantially reduces the waiting time to the US's arrival, then conditioned responding would emerge. The Gibbon–Balsam approach was similarly based on a comparison, but one between the US “expectancies” inside the CS versus in the session overall (see also [Miller and Schachtman, 1985](#)). In a more recent version of this approach, [Gallistel and Gibbon \(2000\)](#) suggested that the comparison is between the calculated rates of US delivery within the CS and at other times. In all of these cases, conditioned responding is said to arise when an assessment of the US time of arrival, expectancy, associative strength, or rate of occurrence is more favorable than that attributed to some relevant comparison condition.

This comparison process explains the emergence of conditioned responding, but, just as in the case of the associative approach, without further assumptions it does not explain how conditioned responding becomes temporally organized. In order to explain this feature of learned responding some authors have proposed that animals also might directly encode the interval between CS and US. Miller and his colleagues describe this in terms of their “temporal coding hypothesis,” but offer little guidance on how such temporal codes develop or arise. Similarly, [Balsam and Gallistel, 2009](#); [Balsam et al., 2010](#); [Ward et al., 2013](#)) suggest that organisms encode the CS–US interval and make subjective estimates of US arrival time based upon that encoding. In both cases, the temporal organization of conditioned responding is thought to reflect some comparison between the current amount of time that has elapsed since trial onset and the subjective estimate of when the US will occur. This framework, at least in spirit, is entirely consistent with earlier descriptions of interval timing in instrumentally conditioned behavior (e.g., [Gibbon et al., 1984](#)). Notice that with this perspective timing is not construed in terms of some associative feature of the CS, per se, as with the associative approach. Indeed, [Balsam and Gallistel \(2009\)](#) and [Balsam et al. \(2010\)](#) explicitly reject the view that associations play any key role at all in behavior. Rather, they assert that animals directly learn the intervals between events and then base their responding upon various computations performed on their representations of the interval relationships formed in the experimental situation. The rapid storage of temporal intervals, according to this approach, presumably reflects the operation of a separate timing process (i.e., a timer) that gives rise to such intervals (e.g., [Gibbon et al., 1984](#)).

Given these quite different ways of approaching the problem of explaining why conditioned responding emerges as it does, how are we to proceed? As noted above, one approach has been to attempt to explain timing phenomena in associative terms. The other has been to attempt to explain associative phenomena in terms of various timing theories (e.g., [Balsam and Gallistel, 2009](#); [Gallistel and Gibbon, 2000](#); [Kirkpatrick and Church, 1998, 2000](#)). However, perhaps another way forward is to ask empirical questions that might lead to an answer that both sorts of processes (associative and timing) contribute to learned behaviors. Several integrative theories along these lines have already been proposed (e.g., [Buhusi and Oprisan, 2013](#); [Church and Broadbent, 1990](#); [Matell and Meck, 2004](#); [Oprisan and Buhusi, 2011](#)), with an eye toward determining how a separable timing system might be understood in associative “connectionistic” terms. More will be said about this later.

One rather basic empirical question, it would seem, is whether timing and associative effects reflect the operation of a single underlying process or dual processes. We have begun exploring this question in several different ways, and the rest of this paper will be concerned with examining some of our findings in three key areas that all point to the validity of a dual-process approach. We will first describe the results of an experiment that we recently completed investigating what we take to be a fundamental prediction of the comparator approaches to learning described above. Then we will describe some data that we take to support the view that learning consists of associations with multiple aspects of the reward, including its time of occurrence, but show that learning involving temporal and non-temporal reward components can be dissociated. Finally, we will present some data to support the dual-process approach, where temporal and non-temporal learning processes may interact to describe behavior in interesting ways.

## 2. Does conditioned responding reflect a comparator process?

We start with the question of whether associative learning can always be reduced to a special instance of a timing process. If it can

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