contributors. Some adopt the tried and trusted method of quantitative experimental psychology, but others adopt a more discursive, qualitative approach, and some are purely descriptive, presenting modeling environments with no attempt at evaluation. One might view this methodological pluralism as a positive sign of a community that is open to ideas from a variety of sources. A less generous view is that it is symptomatic of a field that has no clear direction. My feeling is that it is suggestive of a field that has yet to mature. The discursive qualitative analysis has an important role in generating hypotheses, but the established methods of quantitative experimental psychology appear to offer the most hope for specifying robust principles that may be applied in the development of pedagogically sound computer-assisted learning environments.

In sum, this is a book with two significant weaknesses. It sidesteps important issues, such as the nature of mental models, and it makes limited reference to some relevant literatures. However, these weaknesses do not fundamentally undermine the text. Indeed, they are compensated for by the serious application of the methods, and in some cases even the results, of cognitive science to science education. This is an important area for cognitive science applications, one where more work would be welcome.

Richard P. Cooper
School of Psychology, Birkbeck
University of London
Malet Street, London WC1E 7HX
E-mail: R.Cooper@bbk.ac.uk

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A Challenge to the Standard Interpretations of Conditioning and Choice

The Symbolic Foundations of Conditioned Behavior

By Charles R. Gallistel and John Gibbon. Mahwah, NJ: Erlbaum, 2002. 196 pp. Cloth, $49.95.

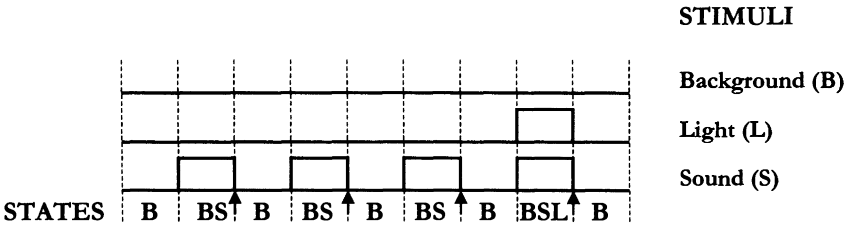
Most readers of introductory textbooks, advanced textbooks on associative learning, and even primary research on conditioning and choice would assume that there is general agreement that learning involves the formation of associations that are strengthened by reinforced practice. Consider, for example, Pavlov's procedure with dogs in which a previously neutral stimulus (e.g., a metronome), followed by an unconditioned stimulus (e.g., food), led to the development of conditioned responses (e.g., salivation). The standard interpretation is that this procedure leads to the development of "associative connections" that have "strength," and various manipulations (such as partial reinforcement, nonreinforcement, magnitude of reinforcement, and delay of reinforcement) affect the strength of the associative connections that are related to the observed behavior. An alternative interpretation proposed by Gallistel and Gibbon is that Pavlov's procedure leads to the learning of time intervals, such as the interval between the onset of the metronome and the delivery of the food, and combinations of the internal representations of these intervals, are related to the observed behavior. The authors refer to this as a "new conceptual framework" (p. 156). Whether or not it is novel, it is a very different from the standard interpretation.

The theory

A conditioning procedure specifies the time of occurrence of the onset and termination of all stimuli and the time of occurrence of the reinforcer. According to the authors, in such a procedure the animal must decide whether to respond and when to respond. They propose that the animal first uses Gallistel's rate expectancy theory (RET) to decide whether to respond and, if the decision is to respond, uses Gibbon's scalar expectancy theory to decide when to respond.

Gallistel's RET is described in his book on the organization of behavior (Gallistel, 1990) and in a *Psychological Review* article (Gallistel & Gibbon, 2000) and has been implemented as a spreadsheet model (Gallistel, 1992). In the 1990s very few articles made use of RET. Many readers may find the theory to be difficult to understand, but it is worth the effort to do so because it provides explicit rules for predicting whether responses will occur.

Consider a procedure in which multiple stimuli occur (such as a light and a sound) both alone and together (Figure 1). It is useful to distinguish between states of the environment, which may consist of a combination of stimuli, and the stimuli themselves. The possible states of the environment are B, BS, BL, and BSL, where B = background alone, BS = background and sound, BL = background and light, and BSL = background, sound, and light. If reinforcers (indicated by arrows) occur in one or more of the states, how should they be credited to the stimuli background (B), sound (S), and light (L)? RET assumes that animals can make an accurate estimate of the reinforcement rate in each state (the number of reinforcers in a state divided by the duration in each state). Now the problem for the animal is to estimate the reinforcement rate in each stimulus, based on the observed reinforcement rate in each state and the "additivity principle" that the sum of the estimated rates in each stimulus is equal to the sum of the observed rates in each state. Thus, the observed rate in each state can be partitioned into a sum of rates due to the component stimuli. In many procedures this leads to n equations in n unknowns, which can be readi-



	REINFORCEMENT RATES	
STATES	OBSERVED	ESTIMATED
Background (B)	B = 0/5 = 0	$\lambda_B = 0$
Background + Sound (BS)	BS = 3/3 = 1	$\lambda_B + \lambda_S = 1$
Background + Sound + Light (BSL)	BSL = 1/1 =1	$\lambda_B + \lambda_S + \lambda_L = 1$

Figure 1. Rate expectancy theory applied to a particular procedure

ly solved by Gaussian elimination. In the example in Figure 1, elementary methods show that $\lambda_B = 0$, $\lambda_S = 1$, and $\lambda_L = 0$. (In cases in which multiple solutions are possible, the minimum number of predictors is used, and if the estimated rate in the background is less than the reciprocal of the time in the background, the estimated rate is set to the reciprocal of the time in the background.) The general solution of the rate estimation problem that is provided did not define basic operations such as matrix inversion or provide a rationale for its use. If matrix methods are used for Gaussian elimination, the description in a linear algebra textbook should be used (Strang, 1988). The problem for most readers will be how to write down the equations for any given procedure, not how to solve the simultaneous equations.

The assumption is that animals continuously update their estimates of the reinforcement rates due to each stimulus and, if the rate attributed to a stimulus is sufficiently greater than the rate attributed to the background, acquisition will occur. The ratio comparison is $(\lambda_{CS} + \lambda_B)/\lambda_B > \beta$, where λ_{CS} is the estimated reinforcement rate during a conditioned stimulus (CS), λ_B is the estimated reinforcement rate in the background, and β is a threshold set by the animal. One of the great strengths of this analysis is that it contains only a single free parameter (β) for any procedure.

When the "whether" criterion has been met, Gibbon's scalar expectancy theory (SET) begins to operate. In the 1990s this theory was used extensively, and the book provides a clear treatment of the essential ideas of the theory along with a large number of useful figures. SET may be stated as a set of principles, including the proportionality principle of a linear relationship between the mean and the interval; the scalar principle of a linear relationship between the standard deviation and the interval; Weber's law for timing, which is the constancy of the coefficient of variation (i.e., the ratio of the standard deviation to the mean); and time scale invariance, in which there is superposition of normalized functions (Gibbon, 1977). Alternatively, a process model involving clock, memory, and decision rules may be used to implement SET (Gibbon, Church, & Meck, 1984).

Synopsis

The book consists of chapters on response timing; acquisition; cue competition and inhibitory conditioning; extinction; backward, secondary, and trace conditioning; and operant choice. Each of these chapters contains clear descriptions of procedures and results and interpretations in terms of the time intervals between stimuli and reinforcers. The final chapter is titled "The Challenge for Associative Theory." It provides a clear contrast between the standard interpretations based on associative strengths and the proposed interpretations based on time intervals between events.

The data come from different species (rabbit, rat, pigeon, and monkey) and a wide range of experimental procedures. The positive reinforcement procedures include fixed interval schedules of reinforcement, the peak procedure, autoshaping, and choice. The aversive reinforcement procedures include the conditioned emotional response, conditioned freezing, avoidance responding, and eyelid conditioning. No critical distinction is made between operant conditioning procedures, in which the reinforcer is contingent on a response, and classical conditioning procedures, in which it is not. In both cases, the focus is on the time intervals between events (stimulus onset, stimulus termination, and reinforcer delivery). By using evidence from different species and procedures, the authors are clearly indicating that the framework they are describing is widely applicable.

This book is based on Gallistel's 1997 MacEachran lectures at the University of Alberta and the authors' article in the *Psychological Review* (Gallistel & Gibbon, 2000). They report that the book is "based closely on" this article and that "most of the figures and much of the text first appeared there" (p. vii). The book provides essentially the same information as the article in *Psychological Review*. About 5% of the 230 references in the book were not in the article. Twenty of the 50 figures are new; 7 of these were based on data from an article that demonstrated rapid learning of changes in reinforcement conditions (Gallistel, Mark, King, & Latham, 2001), and most of the others are diagrams of procedures. These diagrams, some of the revisions, and the division of the material into seven chapters make the book more accessible than the article.

Originality of the book

The general conceptual framework of this book is that the time intervals between events (stimuli, responses, and reinforcements) are learned during a conditioning procedure, and the behavior may be predicted on the basis of these time intervals. The authors write, "In the preceding chapters, we have presented timing models that place our understanding of Pavlovian and operant conditioning in a new conceptual framework" (p. 156). In my opinion, the general conceptual framework is compatible with the views of Pavlov (1927) and Skinner (1938) but not with the interpretations of their views described in most secondary sources.

Pavlov studied three duration discrimination procedures: temporal, delay, and trace conditioning. In temporal conditioning, an unconditioned stimulus (such as food) is delivered at regular intervals; in delay conditioning an unconditioned stimulus is delivered at a fixed time after the onset of a stimulus (such as metronome); and in trace conditioning an unconditioned stimulus is delivered at a fixed time after the termination of a stimulus. In all cases there is a fixed time interval between some event (food delivery, stimulus onset, or stimulus termination) and the next food delivery. In all cases, the magnitude of the conditioned response (in this case, salivation) increased as a function of time since the event. With respect to temporal conditioning, Pavlov concluded, "When we come to seek an interpretation of these results, it seems pretty evident that the duration of time has acquired the properties of a conditioning stimulus" (Pavlov, 1927, p. 41). Skinner expressed a similar opinion about temporal conditioning: "The discriminative stimulus is the complex stimulation arising from the presentation of a pellet of food and its ingestion plus the lapse of time" (Skinner, 1938, p. 271).

The specific conceptual framework of this book is the combination of Gallistel's RET and Gibbon's SET to account for the results of a wide range of procedures. This is certainly a major original contribution, but one that undoubtedly will be superseded by other theories.

Strengths of the revised interpretations of conditioning and choice

Those who are not experts in the interpretation of behavior in conditioning procedures may wonder whether it makes any difference whether an animal is forming associations with different strengths or learning different time intervals. In the final two paragraphs of the book, the authors provide two excellent answers to this question. The new conceptual framework that challenges the standard interpretations should lead to vigorous new programs of research (p. 176), and it will provide neurobiologists with some useful guidance in their attempt to identify the cellular and molecular bases of learning and memory. There is a definite possibility that the standard interpretation of conditioning has misled neuroscientists in their attempt to correlate activity of the nervous system with behavior.

Many theories are designed to apply to a limited range of procedures. One of the strengths of the present interpretation is that it is designed to apply to a wide range of procedures, including classical conditioning, operant conditioning, and choice, which are usually explained with very different theories, such as the Rescorla–Wagner model, the mathematical theory of reinforcement, and the matching law. Gallistel and Gibbon's theory is stated in terms of a quantitative model that is sufficiently clear that it can be readily evaluated with respect to its precision, flexibility, and generality.

Weaknesses of the revised interpretations of conditioning and choice

Although the book provides a guide to essential features of a theory of conditioning and choice, the specific theory has serious weaknesses.

It perpetuates an artificial separation between conditioning and timing by using one theory for acquisition and extinction (RET) and a fundamentally different theory for timing (SET). RET is based on mean reinforcement rates in different environmental states (combinations of background and experimenter-controlled stimuli); SET is based on individual time intervals between events (state transitions, such as stimulus onset and reinforcement delivery). The proposal that an animal decides whether to respond in the presence of a CS before it can decide when to respond during the CS is plausible, but there is no evidence that the acquisition of stimulus discrimination is completed before the acquisition of temporal discrimination begins. A theory that predicted when a response would occur would have no need for an additional theory to account for whether it would occur.

A theory that can be used to explain the data and also a large number of other patterns of behavior may be called a flexible theory. Such flexibility limits the explanatory power of the theory. The predictions of RET are determined completely by the procedure and a single threshold parameter. It is designed to account for cue competition effects (such as blocking) and it does so, at least qualitatively. However, it would not account for any cue facilitation that might be observed. If such facilitation does not occur, this inflexibility would be a strength of the theory, but if it does occur, it would be a weakness. There is a danger that investigators' search for parameters of procedures that lead to cue competition results because cue facilitation results would be incompatible with most previous research and the prevailing theories. In contrast to those of RET, the quantitative predictions of SET depend on the setting of many parameters. They include the latency to start and stop the clock, the clock speed, the memory storage constant, and the threshold. Each has a mean, standard deviation, and distribution form (usually assumed to be a normal distribution).

RET may be used to make qualitative predictions of results (such as blocking) and quantitative analyses of particular indices of behavior (such as trials to a criterion of learning), but it has not been used to make quantitative predictions of multiple measures of behavior. This theory is designed to account for the point at which responding begins during acquisition training and the point at which responding ends during extinction training. It is not designed to account for gradual changes in response rate of a learning curve during acquisition or extinction. SET is designed to account for the relative (not absolute) response rate that occurs after the acquisition criterion has been reached and before the extinction criterion has been reached. Neither RET nor SET accounts for response rate. A theory of conditioning should be able to account for absolute response rate.

The proposed theory may not lead to correct predictions of behavior in many procedures. For example, consider the Pavlovian procedures of temporal conditioning, delay conditioning, and trace conditioning. Temporal conditioning consists of the presentation of reinforcement at regularly spaced times in an unchanging background. Based on RET, an animal could estimate the background reinforcement rate, but acquisition requires a comparison of two rate estimates. Without meeting an acquisition criterion, the animal would not begin to use SET to produce the observed temporal gradients of responding between the successive reinforcers. In delay conditioning all the reinforcers occur at the end of a stimulus. Based on RET, an animal could estimate the background reinforcement rate (which would approach zero) and a stimulus reinforcement rate (which would be much higher). Thus, when meeting the acquisition criterion, the animal would begin to use SET to produce the observed temporal gradients of responding from the onset of the stimulus to the reinforcer. The animal would have no basis to use SET to produce the observed temporal gradients in the absence of the stimulus. In trace conditioning all the reinforcers occur in the absence of the stimulus. Based on RET, the background rate would be higher than the stimulus rate. This does not lead to the observed temporal gradients that are related to the intervals between stimulus onset and reinforcer, between stimulus termination and reinforcer, and between successive reinforcers.

Influence of the book

This book is designed to be a challenge for associative theory. In the final chapter it lists the "standard answers" and the "timing answers" to 16 basic questions, such as "Why does the conditioned response (CR) appear during conditioning?" (p. 156). The book provides the reader with support for the timing answers to each of these questions. Many experts on conditioning may not be much influenced by this book. They may reject the theory because it makes some counterfactual predictions, although it is usually much easier to fix a precise theory than a vague one; they may regard the learning as temporal intervals as part of the content of conditioning that can be put into a separate chapter of a textbook on learning; they may note that their goal is not to account for the behavior of animals based on the procedures but to understand the underlying mechanisms of behavior; they may focus on nontemporal factors that affect learning and performance such as stimulus salience, stimulus similarity, and motivational effects; or they may reject the theory because it is described in terms of cognitive intervening variables.

Although the authors consistently emphasize that time intervals are learned, not strengths of association, I found the book to be a proposal for a compromise between a conditioning theory and a timing theory. Standard conditioning theories, such as the Rescorla–Wagner model, are designed to account for acquisition and the content of learning based on the analysis of the reinforcement rate in different stimulus states. The authors propose the use of RET to account for acquisition and the content of learning based on the analysis of the reinforcement rate in different stimulus states. Standard timing theories, such as scalar timing theory, are designed to account for the pattern of responding on the basis of analysis of reinforcement as a function of time since stimulus transitions (e.g., the onset or termination of a light or the delivery of food) that are used as time markers. The authors propose to do this also.

The ideas in this book are likely to have a large influence on the study of conditioning and timing, but the proposed compromise probably will not be widely accepted. Experts in conditioning may focus on the nontemporal aspects of their procedures and continue to use notation (such as "A+" for a reinforced stimulus state) that does not refer to temporal intervals; they may not record and make available in a data archive the time of each stimulus, response, and reinforcement so that it will not be possible to reanalyze the results of their procedures in terms of timing theories. Others may pursue the essential ideas that are in this book and search for the determinants of learning of response patterns and response rate that may apply to many different procedures and many different response measures (Kirkpatrick & Church, 2003).

Russell M. Church
Brown University
Department of Psychology, Box 1853
89 Waterman St.
Providence, RI 02912
E-mail: Russell_Church@Brown.edu

Notes

Preparation of this review was supported by a National Institute of Mental Health Grant No. MH44234 to Brown University. The author appreciates the useful discussion of issues described in this review with Paulo Guilhardi, Richard Keen, Mika MacInnis, and Steven Seow.

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