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Chapter 1:
Simultaneous Temporal Processing[*]

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Abstract

There is considerable evidence that animals can time multiple intervals that occur separately or concurrently. Such simultaneous temporal processing occurs both in temporal discrimination procedures and in classical conditioning procedures. The first part of the chapter will consist of the review of the evidence for simultaneous temporal processing, and the conditions under which the different intervals have influences on each other. The second part of the chapter will be a brief description of two timing theories: Scalar Timing Theory and a Packet Theory of Timing. Scalar Timing Theory consists of a pacemaker-switch-accumulator system that serves as a clock, a memory that consists of examples of previously reinforced intervals, and a decision process that involves a comparison of ratios to a criterion; the Packet Theory of Timing consists of a conditional expected time function that serves as a clock, a memory that consists of weighted sums of these values, and a probabilistic decision process that produces packets of responses. Both of these theories will be applied to an example of simultaneous temporal processing by rats, and will serve as the basis for some general comments about the basis for selecting and evaluating quantitative theories of timing.

Introduction

Rats, pigeons, and other animals readily learn to make time discriminations in the range of seconds to minutes. Such interval timing is typically demonstrated with fixed-interval procedures, but can also be seen in temporal discrimination procedures in which animals are trained to produce one response following an interval of a short duration and another response following an interval of a long duration (for example, see Stubbs, 1968).

In a fixed-interval schedule of reinforcement, the first response of an animal following a fixed interval of time (such as 60 s) is followed by food. As a result of such training, animals readily learn to respond more rapidly late in the interval than early in the interval (for example, see Catania & Reynolds, 1968). In a standard operant fixed-interval schedule of reinforcement, the fixed interval is defined as the time

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from the delivery of food until the availability of the next food. Alternatively, if a stimulus precedes the food, the interval may be specified from the onset of a stimulus until the availability of the next food. Whether the time marker is the previous food or stimulus onset, the next food is delivered contingent upon the response.

Variations on the fixed-interval procedure have been undertaken to determine whether animals can simultaneously time multiple intervals at once. In a segmented fixed-interval procedure (described in further detail below) there are two potential time markers, the event that marks the beginning of the fixed interval, and the event that marks the beginning of a segment. It is possible that an animal can time both the fixed interval and the segment simultaneously. The segmented fixed-interval procedure and its major results will be discussed in the first portion of the chapter.

In a search of the PsychINFO database for the years between 1887 and 2002, only five articles were found in which the phrase "simultaneous temporal processing" appeared in the title or the abstract. The first of these was an article by Meck and Church (1984). The other four articles that used this phrase in the title or the abstract included either Meck or Church as one of the authors (Church, 1984; Meck, 1987; Olton, Wenk, Church, & Meck, 1988; Meck & Williams, 1997). Based on these facts, one might assume that there is little evidence for simultaneous temporal processing, but that would be mistaken. Many standard conditioning experiments contain multiple time markers that can be timed simultaneously. Although most of these procedures were not explicitly designed to produce simultaneous temporal processing, there is ample opportunity for such timing to occur. The second portion of the chapter will discuss the form of simultaneous temporal processing under widely implemented standard conditioning procedures.

The segmented fixed-interval procedure

One variant of the fixed-interval procedure is to add another stimulus during the interval. This procedure, which will be referred to as a "segmented fixed-interval procedure," has been used for at least three different purposes: as a test of the chaining hypothesis, as a test of the conditioned reinforcement hypothesis, and as a test of the simultaneous temporal processing hypothesis. Although all the experiments to be described used a comparison of a standard fixed-interval procedure with a segmented fixed-interval procedure, they differed in many ways. Procedures were used in which the fixed interval was specified from the delivery of the previous food, and also procedures in which the fixed interval was specified from the onset of a stimulus; in some procedures the onset of a segment was delivered at a fixed time while in other procedures it was delivered following the first response after a fixed time; both pigeons and rats were used; the duration of the intervals differed considerably. The fixed intervals ranged from 50 s to 60 min; the duration of the segment stimulus varied from 0.7 s to 50 s; and the duration of the segments varied from 10 s to 4 min. Despite these differences in durations and the differences in the interpretations of the results, the response gradients in the experiments with the segmented fixed-interval procedures were similar.

As a test of the chaining hypothesis of fixed-interval performance

In a fixed-interval procedure, the mean response rate of the animal increases as a function of time. Although it might be natural to assume that “time“ was the independent variable, there has been an extensive and continuing effort to identify the observable, or at least potentially observable, responses that occur during the time interval that may serve as discriminative stimuli. Behavior in a fixed-interval procedure can be characterized as a series of responses, and the assumption is that reinforcement strengthens responses that occurred shortly before its delivery more strongly than responses that occurred earlier. The chaining hypothesis is that each link in the behavioral chain acts as a discriminative stimulus that controls the response rate during the next link. Thus, the series of responses may serve as a mediating behavior between the successive deliveries of food. This is known as the chaining hypothesis of fixed-interval performance (Keller & Schoenfeld, 1950). One test of the chaining hypothesis is to present a stimulus during the fixed time interval that disrupts performance during the stimulus. According to the chaining hypothesis, such a stimulus should also affect the overall increase in mean response rate as a function of time.

In one experiment, four pigeons were trained on a fixed-interval procedure in the first phase and a segmented fixed-interval procedure in the second phase (Dews, 1962). In the fixed-interval procedure, food was available 500 s after the previous food delivery. In the segmented fixed-interval procedure, the houselight was off for 50 s, on for 50 s, etc. throughout the 500-s interval from food until the availability of the next food. This segmented fixed-interval procedure is illustrated at the top of Figure 1.

The results of the experiment are also shown in Figure 1. The independent variable is time in seconds since the last delivery of food; the dependent variable is response rate as a proportion of the maximum response rate. During the first phase of fixed-interval training (open squares with dotted lines), the mean response rate increased as a function of time. This pattern is often referred to as a “scallop.” During the second phase with segmented fixed-interval training, there was a marked decrease in response rate when the houselight was off. The use of a single measure of response rate during each segment obscures any gradient of responding within segments, but gradients following the onset of a segment stimulus can be seen in the results of the next two experiments to be described (Figures 2 and 3).

This reduction in response rate when the houselight was off could have occurred for many reasons. It may have been a disrupter (Pavlovian external inhibition); it may have been because food was never delivered when the houselight was off (Pavlovian discriminative inhibition); or it may have been due to the difference in salience of the presence or absence of the houselight. For the test of the chaining hypothesis, the cause of the reduction in response rate when the houselight was off relative to when the houselight was on was not important. The critical observation was that, during the segmented fixed-interval procedure, the mean response rate in the presence of the houselight increased as a function of time, i.e., the scalloped pattern remained. Apparently, the maintenance of this temporal gradient of responding did not require the maintenance of responding during the time that the houselight was off. This finding, coupled with the fact that the response rates during the terminal segments were approximately the same in the FI and the segmented FI conditions, was evidence against the chaining hypothesis. The temporal gradient could be maintained in the absence of mediating responses. A series of studies by Dews increased generality for these results and provided additional support for these conclusions (Dews, 1965a, b, 1966, 1970).

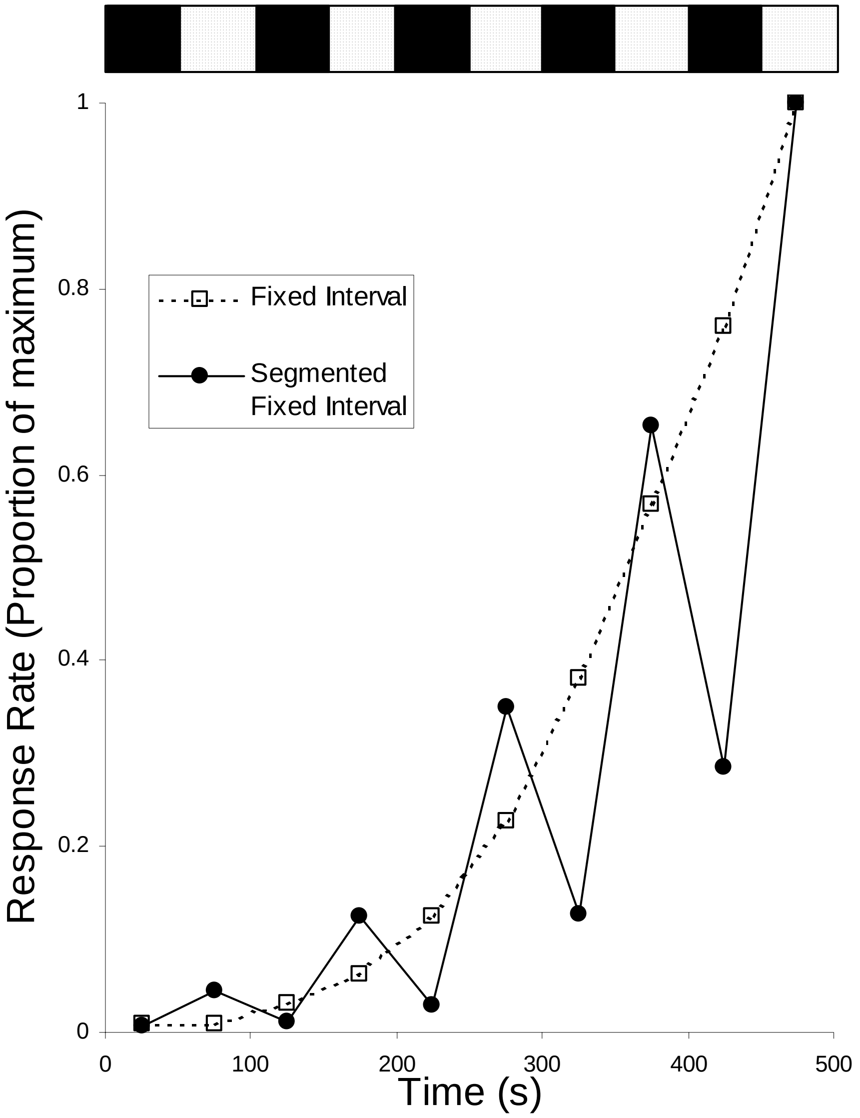

Figure 1: Relative response rate as a function of time since food in a fixed-interval procedure (open squares) and a segmented fixed-interval procedure (solid circles). The segmented fixed-interval procedure is illustrated at the top of the figure: A light was off during the dark intervals and on during the light intervals. Redrawn from Dews (1962).

As a test of the secondary reinforcement hypothesis

A primary reinforcer is normally defined as something that satisfies a biological need, such as hunger. Thus, food is a primary reinforcer. A conditioned reinforcer may be created by pairing a previously neutral stimulus with a primary reinforcer. In the segmented fixed-interval procedure, food is delivered in the presence of one of the segments. Thus, the segment, and others like it, should be conditioned reinforcers and would serve to reinforce behavior. One interpretation of the behavior of animals in a segmented fixed-interval procedure is that the behavior is maintained by conditioned reinforcement.

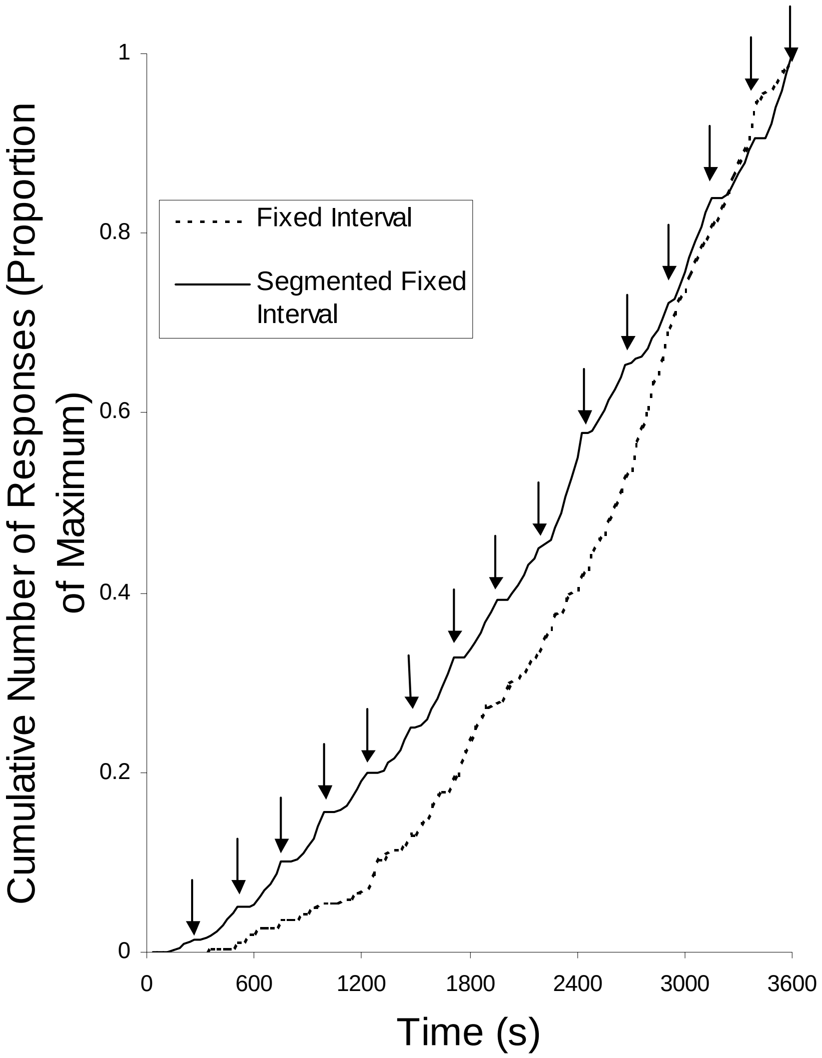

Figure 2: Relative cumulative number of responses as a function of time since food in a fixed-interval procedure (dashed line) and a segmented fixed-interval procedure (solid line). The arrows indicate the time at which a 0.7-s light stimulus was presented. Redrawn from Kelleher (1966)

Figure 2 shows the procedure and some results in one experiment with pigeons (Kelleher, 1966). The independent variable is the time since the last food delivery and the dependent variable is the relative cumulative number of responses (the number of responses during a small interval of time, divided by the total number of responses). The arrows indicate the times at which short stimuli (0.7-s lights) occurred. Each segment stimulus was delivered following the first response after a 4-min interval. The data are taken from only a single 60-min interval for the fixed-interval condition (the dashed line), and from the mean of only two 60-min intervals for the segmented fixed-interval condition (the solid line). The response rate is represented by the slope of the cumulative response function. There was a rising slope in the normalized cumulative response function for both the fixed-interval procedure and the segmented fixed-interval procedure. In addition, for the segmented fixed-interval procedure, response rate was low immediately after a segment stimulus, and then higher later in the 4-min interval.

The main purpose of the experiment was to determine whether or not the segment stimuli could increase relative response rate during a long (60-min) fixed-interval schedule of reinforcement, and whether or not they could lead to the development of a within-segment response gradient. Both of these findings were reported, and they were considered to be supportive of the conditioned reinforcement hypothesis. In other experiments in this article, the segment stimulus was not presented at the end of the last segment which was immediately before delivery of the reinforcer. In these experiments, the response gradients in the segments depended on the pairing of the segment stimulus with the food reinforcement. This supported the interpretation that the segment stimulus was a conditioned reinforcer. However, in a more thorough analysis of the determinants of conditioned reinforcement, Stubbs (1971) did not find a difference in performance between presentation of segments paired or not paired with food reinforcement, even when factors such as the animal's history, reinforcement schedule, and reinforcement rate were analyzed. This suggested that the segmented stimulus served as a discriminative stimulus rather than as a conditioned reinforcer.

As a test of the simultaneous temporal processing hypothesis

Meck and Church (1984) attempted to determine whether rats might simultaneously time the segments in conjunction with timing of the fixed intervals. In the first of the seven experiments the first phase consisted of 35 3-hour sessions of fixed-interval training followed by a second phase with 30 3-hour sessions of segmented fixed-interval training. For fixed-interval training, after an interval of 130 s in a dark box, a houselight was turned on. The first lever response after a fixed interval of 50 s delivered a 45-mg pellet of food and turned off the houselight. These cycles were repeated throughout the session. The segmented fixed-interval procedure was the same, except for the addition of 1-s white noise stimuli that occurred at the time of houselight onset, and 10, 20, 30, and 40 s after the time of houselight onset (as shown at the top of Figure 3).

Figure 3 shows the response rate (expressed as a percentage of the maximum response rate) on the last 20 sessions of fixed-interval training and on the last 20 sessions of segmented fixed-interval training. During the fixed-interval training, the mean response rate had the standard increasing gradient, the fixed-interval scallop. During the second phase with segmented fixed-interval training, there was an overall increase in response rate as a function of time since onset of the houselight, but also a clear decrease in response rate at the onset of the white-noise segment stimuli. In terms of relative response rate, the magnitude of the effect increased as the time of the next reinforcement approached.

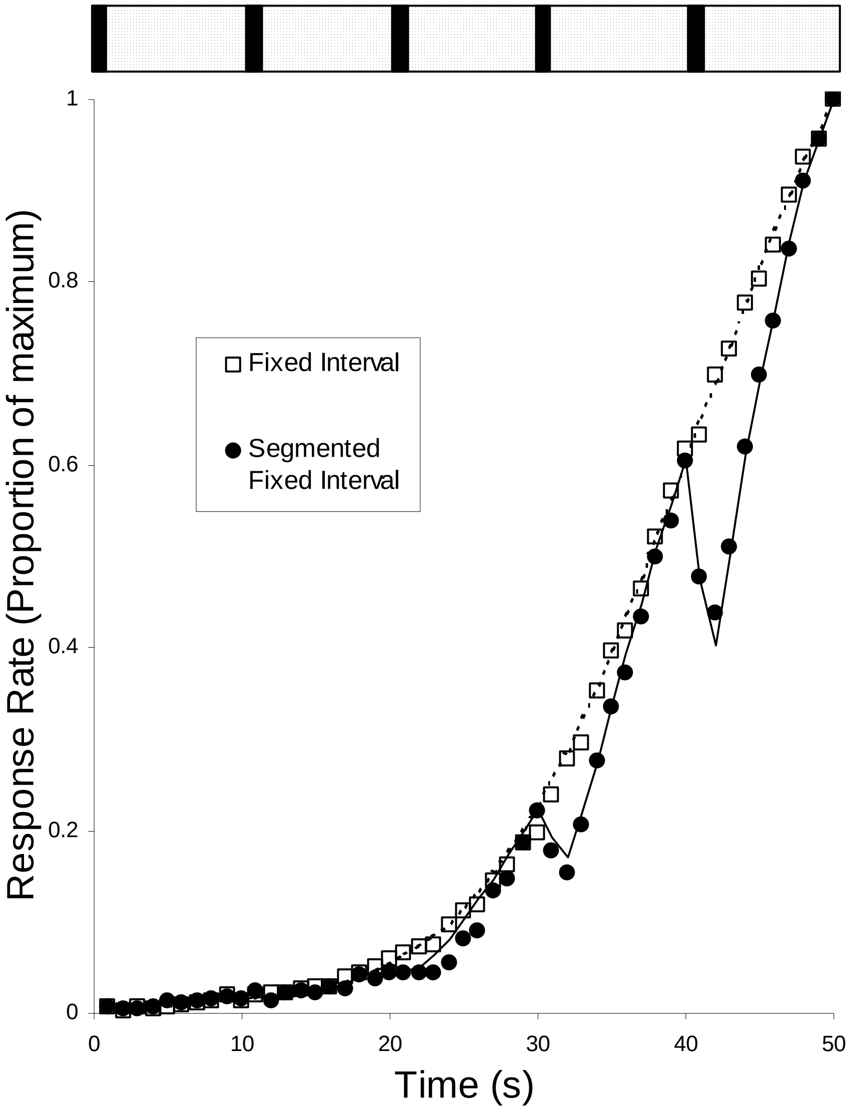

Figure 3: Relative response rate as a function of time since food in a fixed-interval procedure (open squares) and a segmented-fixed interval procedure (solid circles). The segmented fixed-interval procedure is illustrated at the top of the figure: The dark intervals indicate the times at which a 1.0-s white noise stimulus was presented. Redrawn from Meck and Church (1984)

In a second experiment, Meck and Church (1984) repeated the conditions shown in Figure 3, but added one more white-noise segment stimulus during the last second of the interval. The overall and segment gradients were similar to those shown in Figure 3. Other experiments in this article produced similar results with a segmented peak procedure in which the fixed interval and segment stimuli continued beyond the normal time of reinforcement (and reinforcement was withheld), and when the final segment stimulus occurred just before the reinforcer. These results suggest that the onset of the stimulus for the fixed interval, and the onset of a segment stimulus both served as discriminative stimuli for the time at which food would be available.

The main contributions of the Meck and Church (1984) experiments were to describe the problem as one of timing multiple intervals (rather than disruption of a response chain or conditioned reinforcement), and to describe the results of a quantitative model of timing. With this timing perspective it became natural to examine whether the application of scalar timing theory to a single interval could be extended to the timing of multiple intervals. In Figures 1 and 2 the lines merely connected the observed data points, thus facilitating visualization of the pattern of the data. In Figure 3 the dotted and solid lines that were near the observed data points were based on a quantitative theory of timing—scalar timing theory. It is possible that an examination of scalar timing theory will provide some understanding of the basis of simultaneous temporal processing.

Scalar timing theory

The essential principles of scalar timing theory were developed by Gibbon (1977), and they were subsequently used in the development of an information processing model of scalar timing theory (Gibbon, Church, & Meck, 1984). The information-processing model of scalar timing theory contains three major parts: clock, memory, and decision. A clock consisted of a pacemaker, a switch, and an accumulator; the memory was a reference memory for long-term storage of time intervals, and the decision was done by a comparator that could measure the nearness of the current time (in the accumulator) with a remembered time that was sampled from a reference memory. For timing a single interval, all that is needed is a single clock (pacemaker, switch, and accumulator), a single memory, and a single comparator. These parts are shown in the upper left side of Figure 4.

In the fixed-interval procedure mentioned above, when the food was delivered the food onset switch would close, permitting pulses from the pacemaker to enter the accumulator. Thus, if the pacemaker emitted 5 pulses a second with no variability, after 50 s the accumulator would have 250 pulses. If there was some variability in the pacemaker rate, after 50 s the accumulator might have fewer or more than 250 pulses. References memory contained a representation of the number of pulses in the accumulator at times that reinforcement had been received in the past. This is an exemplar memory that contains separate representations for each of the past examples. The decision is based on a comparison of the current accumulator value, which is continually increasing, and the value of a random sample of one element from reference memory. The comparator output depends on a ratio comparison of the two inputs (accumulator and memory) and a threshold criterion. If the current accumulator value is close enough to the value of the sample from memory, a response occurs. Details of this model are described in several sources (Church & Gibbon, 1982; Gibbon, Church, & Meck, 1984; Church, 2003). Four sources of variability were implemented in the simulations: the coefficient of variation (ratio of standard deviation to mean) of the clock, the mean and standard deviation of the threshold criterion, and the probability of inattention. An exhaustive search of the parameter space produced optimal values of the parameters of .25, .20, .10, and .01 for the four parameters, and these same parameter values were used in several experiments. This accounted for over 99% of the total variance in the response rate gradients in the fixed-interval condition, which suggests that, if scalar timing theory is correct, the animals were nearly always attentive to the time, but that there was some clock and threshold variability.

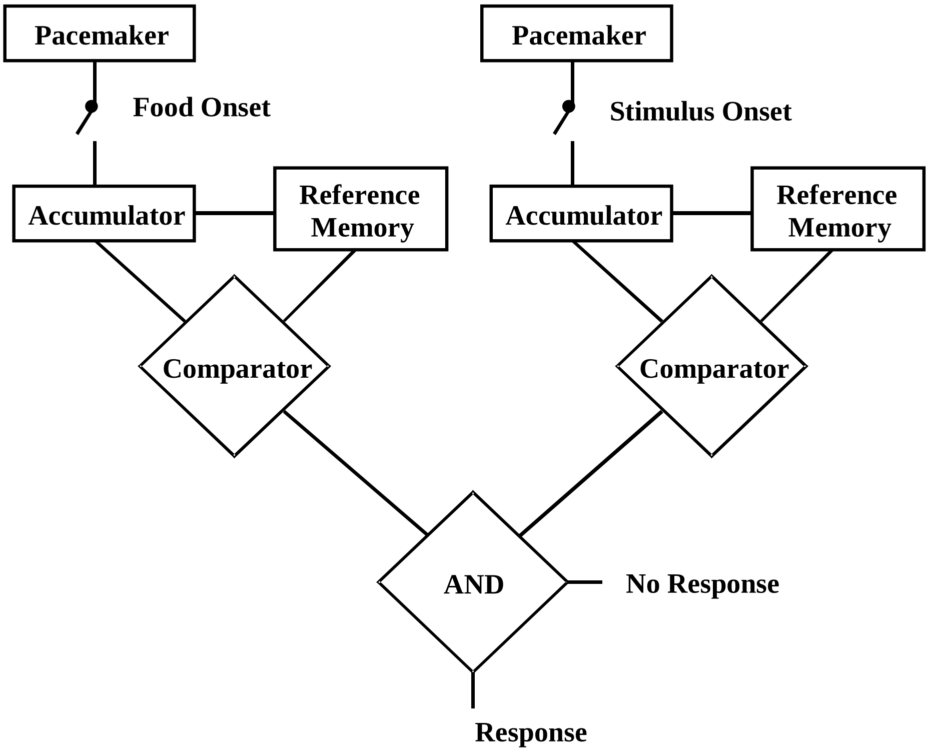

Figure 4: Application of scalar timing theory to the segmented fixed-interval procedure. Two independent clock-memory-decision units are controlled by food onset and stimulus onset. The output of these two units produces a response if both are above a threshold.

In the segmented fixed-interval procedure, the same process with the same parameters was used for the time since food onset, and an equivalent process (but with the addition of a latency-to-close-the-switch parameter, and different parameter values) was used for the time since stimulus onset (the top right part of Figure 4). Thus there was simultaneous timing of the interval since food and the interval since stimulus onset. The output of the two comparators were combined by assuming that the animal attended to the overall interval with some probability, that it attended to the segment interval with some probability, and that these two probabilities were independent. Thus, on some occasions, the rat attended to both intervals, on some it attended to only the overall interval, and on some it attended to neither. This accounted for over 99% of the total variance in the response rate gradients in the segmented fixed-interval condition, which suggests that, if scalar timing theory is correct, the animals were combining information from the overall and segment interval in the determination of whether or not to respond.

Simultaneous temporal processing in conditioning procedures

The performance of animals in the segmented fixed-interval procedure makes it clear that they are able to time two intervals simultaneously. Is this an ability that requires a particular test to be revealed, or is simultaneous temporal processing an ability that may be revealed in standard conditions? The purpose of this section is to make the case that simultaneous temporal processing occurs in many conditioning procedures, including the most standard procedures such as delay and trace conditioning. Variations in the location of the reinforcer in a cycle, in stimulus durations, and cycle durations can also be understood as examples of simultaneous temporal processing.

Location of the reinforcer in a cycle

Two types of conditioning procedures studied in Pavlov's laboratory were delay conditioning and trace conditioning (Pavlov, 1927). In delay conditioning, a stimulus is presented for a fixed duration and a reinforcer is presented at the end; in trace conditioning, a stimulus is presented for a fixed duration and a reinforcer is presented at some fixed time after the termination of the stimulus.

The two procedures diagrammed at the top of Figure 5 are variants of the Pavlovian delay and trace conditioning procedures (unpublished research of M. MacInnis). Eighteen rats were trained in a box with one stimulus (white noise), one reinforcer (a food pellet), and one measured response (head entry into the food cup). A cycle consisted of 20 s with noise and 100 s without noise. These cycles continue throughout a session with food available at the same point during each cycle with a probability of 0.5. The data are shown for cycles in which food was delivered. Nine rats received the delay conditioning procedure before the trace procedure; nine other rats received the treatments in the other order. In the case of delay conditioning, food was available at the end of the stimulus on a random half the cycles (indicated by the first arrow); in the case of trace conditioning, food was available 10 s after stimulus termination on a random half of the cycles (indicated by the second arrow).

The delay procedure provided three time markers (stimulus on, stimulus off, and food delivery). The time from stimulus onset to food availability was 20 s; the time from stimulus termination to food availability was 0 s; and the time from food to food was 120 s. In the delay procedure, the response rate increased as a function of time since stimulus onset; at stimulus termination the response rate declined abruptly; and there was a very small increase in the response rate as a function of time during the last 60 s of the cycle.

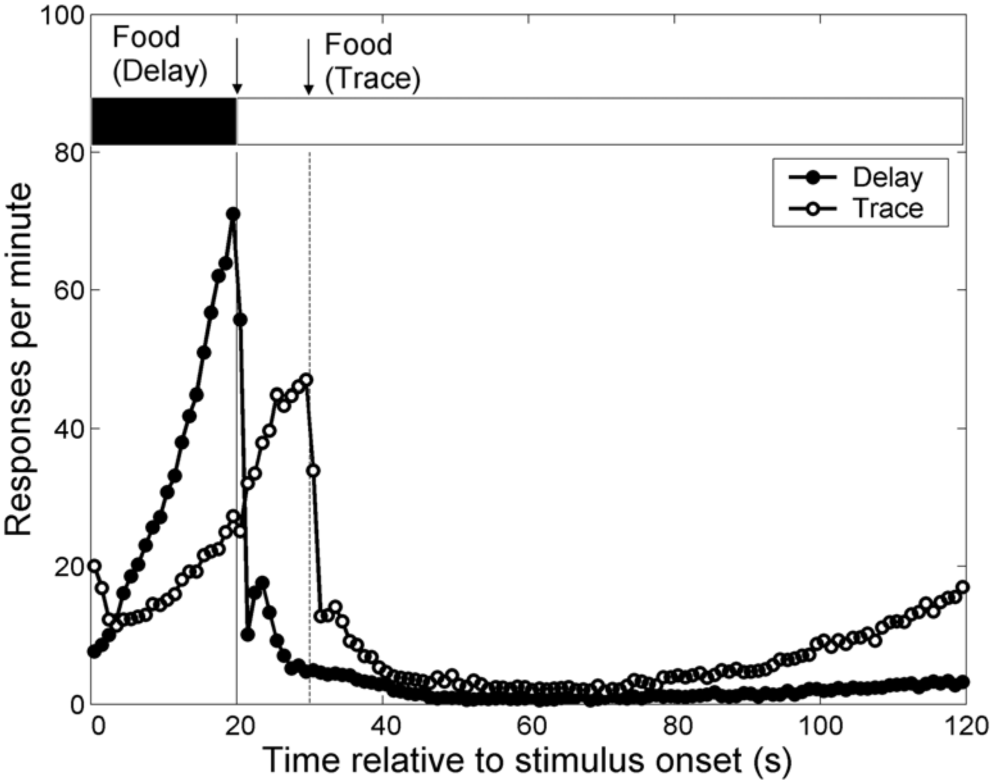

Figure 5: Response rate as a function of time from stimulus onset under a delay and trace conditioning procedure. The procedure is shown in the top of the figure. Based on unpublished research of M. MacInnis

The trace procedure also provided three time markers (stimulus on, stimulus off, and food delivery). The time from stimulus onset to food availability was 30 s; the time from stimulus termination to food availability was 10 s, and the time from food to food was 120 s. Simultaneous timing during the cycle was apparent in the pattern of results shown in Figure 5. In the delay condition there was an abrupt increase in response rate at the onset of the stimulus, a sharp dropoff in response rate at stimulus termination and food delivery, which was followed by a slow rise toward the end of the cycle. In the trace condition there was an increase in response rate at the onset of the stimulus; at stimulus termination it continued to increase, but with a somewhat steeper slope; and at the time of food delivery the response rate declined abruptly, and there was an increase in the response rate as a function of time in the last 60 s of the cycle. The multiple slopes present in the response gradients suggest that the animals were using more than just the food-to-food interval to determine how fast to respond. In addition, the dip in response rate present at the beginning of the cycle for the trace procedure is similar to the dips seen in the segmented peak interval, and presumably is another example of simultaneous temporal processing.

Variations in the stimulus duration and cycle duration

Two variables that affect the speed of acquisition and asymptotic performance of conditioned responses are the duration of the stimulus and the duration of the cycle. The duration of the stimulus is sometimes referred to as the duration of “the trial;” and the duration of the cycle is referred to as the duration of “the trial” plus the duration of “the intertrial interval.” Conditioning may be improved by reducing the duration of the stimulus or increasing the duration of the cycle. The speed of acquisition of autoshaping by pigeons has been found to be approximately the same when the stimulus to cycle duration ratio is the same (Gibbon, Baldock, Locurto, Gold, & Terrace, 1977). This is an example of timescale invariance in which relative, rather than absolute, time intervals control behavior (Gallistel & Gibbon, 2000, 2002).

The effect of variations in the stimulus and cycle duration can be studied with rats using the head entry response. Three recent studies have suggested that both stimulus and cycle durations are relevant, that the ratio of the two is a better predictor of performance than either one alone, but that timescale invariance is only an approximation (Lattal, 1999; Holland, 2000; Kirkpatrick & Church, 2000). These results provide evidence for simultaneous temporal processing.

The general procedure is illustrated at the top of Figure 6. For each animal, the interval between successive deliveries of food is fixed (cycle duration), and the interval between stimulus onset and food is fixed (stimulus duration). Some results from the experiments of Kirkpatrick and Church (2000) are shown in Figure 6. The response rate during the stimulus as a function from stimulus onset is shown for groups with the same cycle duration of 180 s but different stimulus durations and also for groups with the same stimulus duration of 60 s but with different cycle durations. When the cycle duration was 180 s, the temporal gradients were ordered by the stimulus duration (15, 30, 60, and 120 s), and when the stimulus duration was 60 s, the temporal gradients were ordered by cycle duration (90, 180, and 360 s).

The contribution of simultaneous temporal processing is evident in the bottom two panels of the figure, which display the full gradients over the course of the cycle for pairs of groups that received stimulus/cycle duration ratios of .67 or .17. The gradients were not the same for two conditions in which the stimulus/cycle ratio was .67, and they were not the same for two conditions in which the stimulus/cycle ratio was .17. The time of stimulus onset is marked on each function by an arrow. Timing from the prior food delivery can be seen particularly well in the groups with the .17 ratios. Response rates increased gradually prior to stimulus onset and then abruptly changed at stimulus onset so that responding increased more rapidly.

This procedure gave the animal two time cues to use, in order to anticipate when the food would be made available: Stimulus on and food delivery. (Food was always delivered at the time of stimulus termination so this was not a differential cue.) The observed performance is apparently affected by the simultaneous temporal processing of these two intervals. The rats evidently timed from both cues, as seen in the bottom panels of Figure 6, and the response during the stimulus may have been determined by a combined influence of timing from both markers. When the cycle duration was constant, then the additional effect of the stimulus was determined directly by stimulus duration. However, when stimulus duration was held constant (stimulus 60 s groups) variations in the cycle duration might have resulted in difference in the additional amount of responding during the stimulus. A shorter cycle would have produced more responses from the prior food delivery and thus there would be a greater response rate during the stimulus if the rat was simultaneously timing both cues at once.

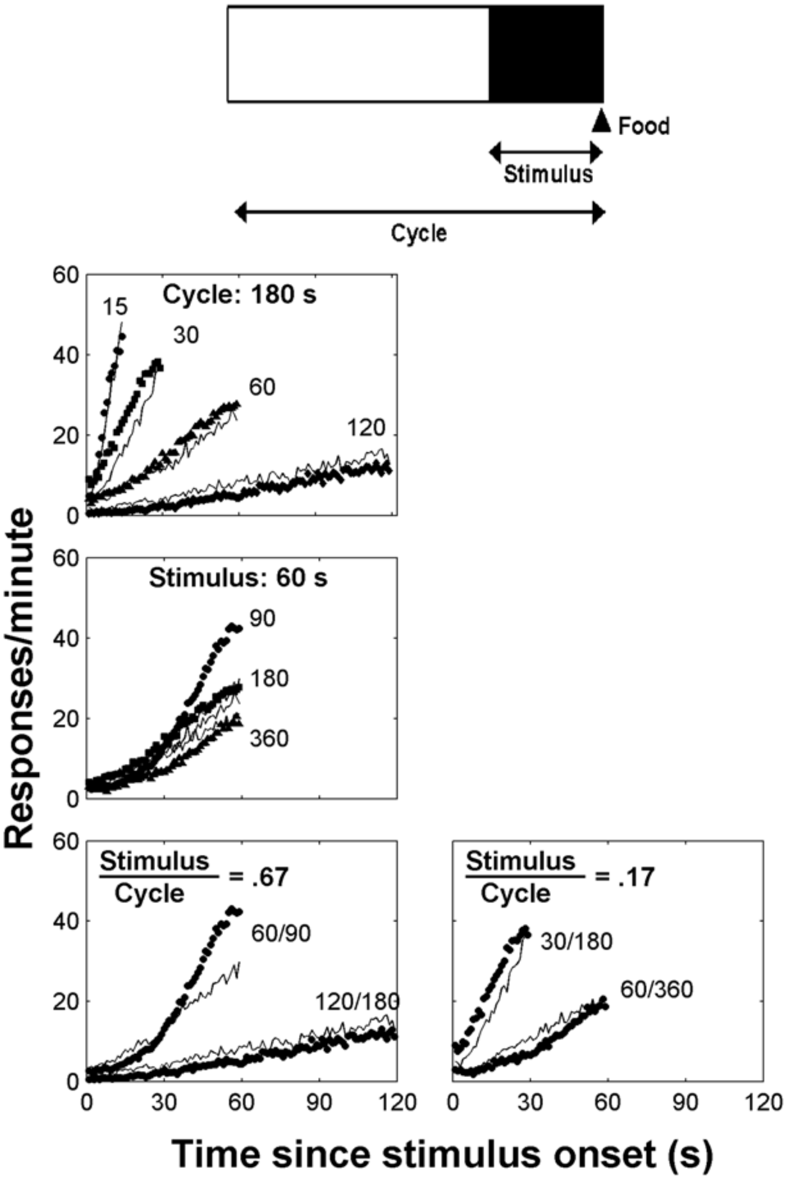

Figure 6: Effect of variations in duration of stimulus and cycle on the response rate as a function of time. Top panel is the procedure. Middle left panel: Effect of stimulus duration with a fixed cycle; Middle right panel: Effect of cycle duration for a fixed stimulus; Bottom data panels: Differences in response rate gradients with constant stimulus/cycle ratios. The thin smooth lines are based on packet theory; the arrows indicate times of stimulus onset (see text). Redrawn from Kirkpatrick and Church (2000).

A formal model of the process, packet theory, is being developed to account for the behavior of rats in procedures involving one or more temporal cues (Kirkpatrick, 2002; Kirkpatrick & Church, 2003). A basic idea is that behavior, such as head entry into a food cup, consists of bouts of responses. A distinction is made between a bout, which is an observed dependent variable, and a packet, which is an intervening variable of the theory. The proposal is that the momentary probability of producing a packet is controlled by the expected time to food. Figure 7 shows an overview of the theory in which the stimulus (stimulus to food interval) was 60 s and the cycle (food to food interval) was 180 s. The top left panel shows the expected time to food, E(t), decreasing from 60 s to 0 s as a function of the time since stimulus onset. The middle left panel shows the same function in memory. If the interval between stimulus and food was not always 60 s, a standard weighted linear combination rule is used to combine the most recent perceived function with the remembered function. The bottom left panel shows a decision function that is determined by the memory function. It is inverted in direction, and normalized to produce a unit area. The three panels on the right provide the same information for the food-to-food interval, and the bottom panel shows the two functions on the timeline for a cycle. As shown in the procedure (at the top of Figure 6) with a 60-s stimulus at the end of a 180-s cycle, the stimulus begins at 120 s. The dependent variable is the probability of a packet of responses. One plausible combination rule for the two functions is a simple summation, which was used.

The results of a simulation of the packet model (with the same parameter settings as used by Kirkpatrick, 2002) is shown by the thin lines near the data points in Figure 6. With these parameters, packet theory provides a good approximation of the effect of stimulus duration, and a good approximation of the failure of constancy of the stimulus/cycle ratio, but it does not show the degree to which the duration of the cycle affected the response rate during the stimulus. This may be improved by increasing the weighting of the cycle effect, or it may indicate that the combination rule is incorrect.

In this analysis, a quantitative theory of timing was used to predict the response rate as a function of time from time markers, and then a simple summation of the response rates was used as the combination rule. There are many plausible ways to combine information from two sources about the time to the next food. One could combine the times in various ways (sum, mean, larger, smaller, etc.) and these operations could be done on any transformation of the timescale. Alternatively, one could use each of the time estimates to the next food to generate response probabilities that could be assumed to be independent and combined in various ways to produce logical outputs such as “and” or “or.” There may be a typical combination rule, or it may be that the combination rule is based on the task demands. Both an empirical and theoretical approach can be useful. The goal is to be able to predict what an animal will do with multiple sources of information about the time to reinforcement, based on knowledge of what the animal will do with each of the sources of information individually.

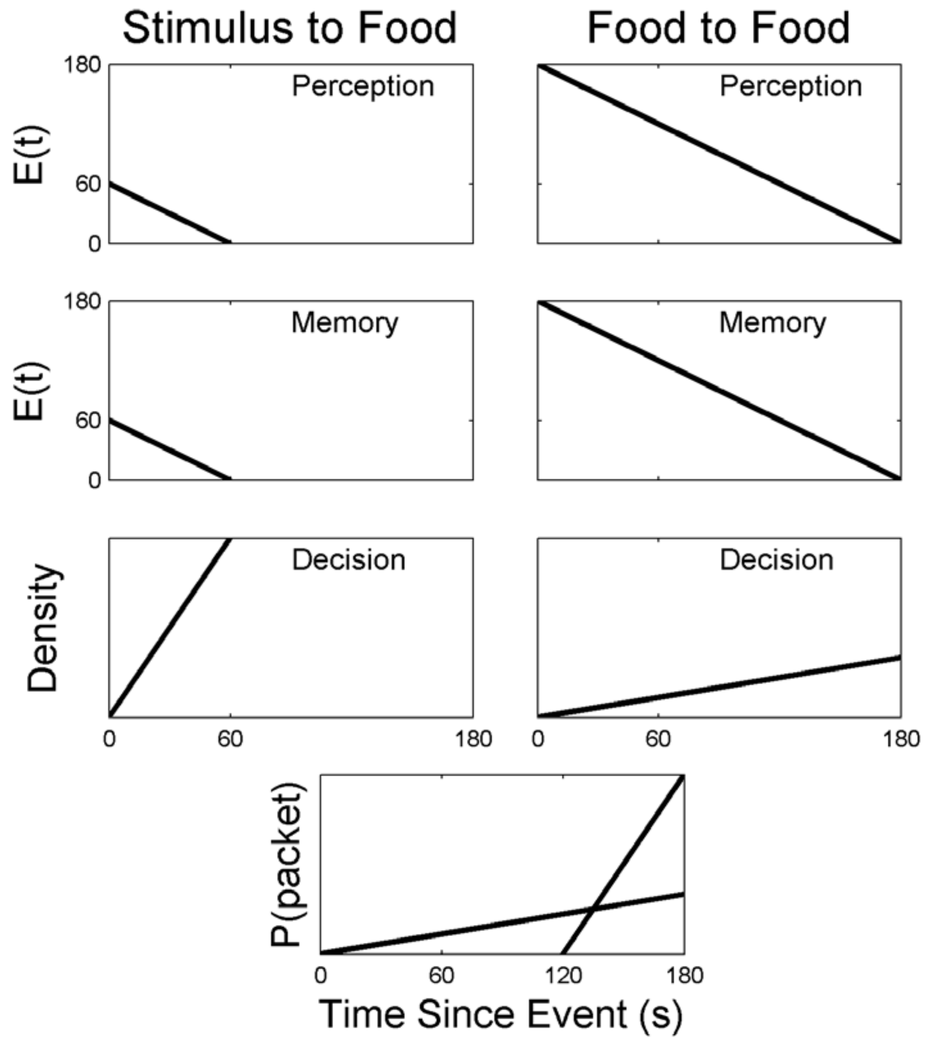

Figure 7: Application of packet theory to simultaneous temporal processing. Two independent functions are produced by stimulus onset and food onset. The two functions, shown in the bottom panel, produce the probability of a packet of responses according to an additive combination rule. This analysis is based on Kirkpatrick (2002).

Conclusions

The demonstration of simultaneous temporal processing does not require the use of any specialized procedures, such as the segmented fixed-interval procedure. It is likely present in many, if not most, of the procedures used in the study of conditioning and instrumental learning. Although the examples in this chapter were based on the use of constant intervals, introducing variability into the intervals does not eliminate the timing of them (Kirkpatrick & Church, 2003).

Much more work is needed in the development, evaluation, and selection of a theory of simultaneous temporal processing. At present there is no generally accepted quantitative theory of simultaneous temporal processing. Scalar timing theory and packet theory are two candidates, but (perhaps with some modifications) many other quantitative theories of conditioning and timing are also candidate theories that may be developed. An essential feature of any theory of simultaneous temporal processing is the selection of a combination rule for the multiple sources of temporal information.

The criteria for the evaluation of a theory includes much more than goodness of fit. A good theory should be relatively inflexible so that it cannot fit a large number of data patterns that do not occur. Quantitative measures that take into account the inflexibility of a theory are readily available to psychologists. Generality of a theory is also important. This sometimes refers to the formal characteristic of separation of fits of replicable factors from the fits of error factors; but it may also be used to refer to the more informal characteristic of fitting data from many sources. The growth of the availability of data archives (Kurtzman, Church, & Crystal, 2002) and secondary data analysis, may make it feasible to apply a theory of simultaneous temporal processing to a wide range of experimental data.

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