Measures of temporal discrimination in fixed-interval performance: A case study in archiving data

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The primary data of many experimental studies of animal learning and performance consist of the times at which stimuli and reinforcers were delivered, and the times at which responses occurred. The articles based on most of these studies report selected data, either from some sessions or some animals, or summary measures of the animals' behavior. The primary data are sufficient to produce any of the selected and summary measures, but the selected and summarized data cannot produce many of the measures used in other experimental reports. It is now feasible to archive the primary data from animal behavior experiments so that they are accessible for others to perform secondary analysis. The value of such secondary analysis of archived data is described with a case study in which rats were trained on three fixed-interval schedules of reinforcement. The full data set may be downloaded from www.psychonomic.org/archive/.

Many experiments on animal learning and performance consist of discrete events, such as the onset or termination of a stimulus, the delivery of food, or a response that closes or opens a switch or that breaks a photobeam. Investigators of operant conditioning have made extensive use of the cumulative recorder to record the primary data that consist of times of occurrences of these discrete events (Ferster & Skinner, 1957). These records, although extensive, are not in a convenient form for subsequent analysis. In most cases, only selected examples of performance could be presented. To reduce the random error on individual trials of individual animals, most investigators have presented summary measures of behavior averaged across many trials, and sometimes across many animals. Although the primary data can produce all of the summary measures, the summary measures cannot be used to reconstruct all other summary measures. A good quantitative theory of the processes involved in animal learning and performance should lead to the prediction of the primary data (and thus, all summary measures), not just selected summary measures.

The value of archiving primary data will be developed with a case study of an experiment with fixed-interval schedules of reinforcement. In a fixed-interval schedule of reinforcement, a pigeon, a rat, a human, or some other animal receives a reinforcer following a response after a fixed interval following some event, such as food delivery

or stimulus onset. Fixed-interval schedules of reinforcement have been used extensively for many years to investigate the ability of animals to adjust to the temporal regularities of their environment.

A search of the PsycInfo database from 1896 to the present for "Fixed interval" and "Fixed-interval" led to 1,475 references in 171 journals. The articles in *Behavior Research, Methods, Instruments, & Computers (BRMIC)* described computer programs to calculate indices of temporal discrimination (Maurissen, 1978; Maurissen & Inglis, 1978) and to generate interval schedules (Wolach & McHale, 2002). One article described a procedural variation for the use of fixed-interval procedures to separate discrimination of a stimulus and a reinforcer (Woodard & Bitterman, 1974). Other articles used the fixed-interval schedules to evaluate apparatuses for testing visually guided perception and learning in newborn macaques (Sackett, Tripp, Milbrath, Gluck, & Pick, 1971) and training a licking response in bats (Shumake & Caudill, 1974).

The largest number of articles on fixed-interval schedules of reinforcement (334) were published in the *Journal of the Experimental Analysis of Behavior (JEAB)*. The typical response for a pigeon was pecking a lighted disk; the typical response for a rat was pressing a lever. Some articles contained information about the response rate, others contained information about the response pattern, and most articles contained information about both rate and pattern. Table 1 lists the types of measures of behavior used in articles in the *JEAB*.

The primary data from a fixed-interval schedule of reinforcement are the times of occurrence of stimulus onsets and terminations, responses, and reinforcements. The most frequent summary measure is the response rate over extended periods of time, and the least frequent summary measure is a figure showing the time of occurrence of each

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Table 1
Frequency of Use of Different Measures in Articles in *JEAB*
on Fixed-Interval Schedules of Reinforcement

Measure	Frequency	Proportion of Articles
Response rate	254	.760
Cumulative record	190	.569
Temporal gradient	95	.284
Time of <i>n</i> th response	73	.219
Curvature index	20	.060
Time of transition	19	.057
Time of <i>k</i> th percentile	17	.051
IRT distribution	15	.045
Other	7	.021

Note—Number of measures: 690; number of articles: 334.

stimulus onset and termination, response, and reinforcement. This information occasionally has been displayed as the output of an event recorder that puts a distinctive mark on paper moving at a relatively constant rate. This preserves all of the information in the primary data, which allows one to estimate event rates by the density of marks. The cumulative recorder (Skinner, 1938) also preserves all of the information in the primary data, and it provides an important advance over the event recorder because it is easier to read: The horizontal axis represents the cumulative time (as in an event recorder), but there is also a vertical axis that represents the cumulative number of responses. Thus, it is possible to estimate local and global rates by the slope of the line between different points. Although cumulative records are often recorded for all animals throughout an experiment, only selected cases can be published. Partly because of this limitation, various summary measurements of fixed-interval performance have been devised, including both gradients and indices.

Temporal gradients provide information about the mean response rate as a function of the time since some time marker, such as the previous reinforcer or stimulus onset; transition gradients provide information about the mean response rate as a function of time before and after a transition from a low to a high rate.

A single numerical index may also be used as a measure of temporal discrimination. Several indices are based upon temporal gradients, such as the curvature index, the center of the best-fitting ogive, and the scale of the best-fitting ogive. Several indices are based on transition gradients, such as the time of the transition, the mean rate before the transition, and the mean rate after the transition. Several indices are based on the time of a criterion response number, such as the time of the first response, or the time of some criterion percentile response, such as the time of the 25th percentile response (quarter-life), and the time of the 50th percentile response (median). Several indices are based on response rates, such as the mean response rate, the mean response rate during the first 30 sec of the interval, and the temporal discrimination ratio, which is a ratio of a response rate during an interval near the end and near the beginning of an interval.

A single numerical index provides considerable summarization of the data, and different indices provide information about different aspects of performance. A quantitative

model that accounts for the results of a particular index may not provide an account for the results of other indices.

Most experimental studies on fixed-interval performance provide summary information about one or two measures of performance on some sessions (Table 2). From the reported summary measures, it is generally not possible to calculate the unreported summary measures. At present, an investigator would need to repeat the experiment in order to obtain an alternative summary measure. Of course, any of the measures could be readily calculated from the archived primary data. Secondary analysis of such archived data provides a way to determine whether a conclusion based upon one experiment is also supported by the data from other experiments. It also provides a way to verify previous analyses, to determine the consequences of modification of the analyses and, if necessary, to correct errors. In addition, such secondary data analysis can lead to discoveries and may be used for model development. There is a major need for open access on the Internet to primary data from experiments that are well documented and typically linked to published articles. These may be individual Web sites (such as <http://www.brown.edu/research/timelab>) that contain data on which published articles on timing from our laboratory have been based. For archival purposes, however, an institutional repository such as a university or a scientific society is superior because it provides greater assurance of long-term availability of the data.

In addition to the data, tools that facilitate their analysis would be valuable. The supplementary material accompanying the present article provides some of these tools. It makes it possible to immediately reproduce any of the figures in this article or to examine any of the dependent variables for different individuals or sessions. The Matlab code may be used as written to examine any of the measures for any individual (or combination of individuals) for any session (or combination of sessions). Alternatively, the Matlab source code may be modified and used, or the source code may be used as a strict definition of the variables which can be readily duplicated with other programming languages, such as C. A workshop sponsored by the National Institute of Mental Health, focused on data archiving for animal cognition research (Kurtzman, Church, & Crystal, 2002), led to a report with conclusions and recommendations that are currently being implemented and that may apply to other research communities.

Table 2
Frequency Distribution of Number of Different Measures in
Articles in *JEAB* on Fixed-Interval Schedules of Reinforcement

Number of Measures	Proportion of Articles
1	.302
2	.386
3	.212
4	.069
5	.028
6	.000
7	.000
8	.003
Sum	1.000

This article describes 15 measures of temporal discrimination that are applied to the primary data from a fixed-interval procedure. This makes it possible to compare directly reports of experiments that used different dependent variables and to determine whether a quantitative process model applies to the behavior of the animals or only to a restricted range of summary measures of the behavior. The purpose of the article is to demonstrate the feasibility and value of secondary analysis of primary data in animal timing research.

METHOD

Animals

Twelve male Sprague-Dawley rats (Taconic Laboratories, Germantown, NY) were housed individually in a colony room on a 12:12 light:dark cycle (lights off at 8:30 a.m.). Dim red lights provided illumination in the colony room and the testing room. The rats were fed a daily ration that consisted of 45-mg Noyes pellets (Improved Formula A) that were delivered during the experimental session, and an additional 15 g of Formulab 5008 food given in the

home cage after the daily sessions. Water was available ad lib in both the home cages and experimental chambers. The rats arrived in the colony at 35 days of age and were handled daily until the onset of the experiment. Training began when they were 67 days old.

Apparatus

The 12 chambers ($25 \times 30 \times 30$ cm) were located inside ventilated, noise-attenuating boxes ($74 \times 38 \times 60$ cm). Each chamber was equipped with a food cup and a water bottle. Three stimuli were generated from modules (Med Associates, St. Albans, VT). A 70-dB white noise, with an onset rise time and termination fall time of 10 msec, was generated by an audio amplifier (Model ANL-926). The light was a diffused houselight (Model ENV-227M) that could illuminate the entire chamber over 200 Lux at a distance of 3 in. The clicker (Model ENV-135M) was a small relay mounted on the outside of the chamber that was used to produce an auditory click at a rate of 1 per sec. A pellet dispenser (Model ENV-203) delivered pellets into the food cup on the front wall. Each head entry into the food cup was detected by an LED-photocell. A water bottle was mounted outside the chamber; water was available through a tube that protruded through a hole in the back wall of the chamber. Two Gateway Pentium III/500 computers running the Med-PC for Windows Ver-

Figure 1. Cumulative records. Cumulative number of responses as a function of time in seconds. The panels show 4 min of data from individual rats during three fixed-interval schedules of reinforcement (FI 30, FI 60, and FI 120 sec).

sion 1.15 using Medstate Notation Version 2.0 (Tatham & Zurn, 1989) controlled experimental events and recorded the time at which events occurred with 2-msec resolution.

Procedure

The rats were randomly partitioned into three groups of 4 rats that were trained under a 30-, 60-, or 120-sec fixed-interval schedule of reinforcement. A cycle consisted of a 20-sec interval with discriminative stimuli off, followed by the fixed interval with a discriminative stimulus on. Stimuli were given such that at least 1 rat in each group had each stimulus. With this restriction, each rat was randomly assigned to one of the three stimuli. Food was primed at the end of a fixed interval. Immediately after the next head entry into the food cup (measured as the time of breaking a photobeam in the food cup), food was delivered, the discriminative stimulus was turned off, and the next cycle began. A session consisted of 60 cycles or 150 min, whichever came first. Each rat had 10 experimental sessions.

Results

Three measures of temporal discrimination in fixed-interval performance make use of a vector of values. These

are cumulative records, temporal gradients, and transition gradients.

Cumulative Records

The cumulative records, which provide a way to visualize the results without summarization, consist of a graph of the cumulative number of responses as a function of time. The points are joined together by a staircase line in which the line is horizontal between responses and increases by one unit whenever a response occurs. A slash across the line represents the times of food delivery. The intervals from one food delivery to the next are 30, 60, and 120 sec under the three fixed-interval conditions. Figure 1 shows the cumulative record for about 240 sec of the 10th session for each of the rats. In most cases, there is a pause after reinforcement, followed by a relatively constant rate of response. This transition between a low response rate interval and a high response rate interval is known as the "break-run" pattern of responding.

Figure 2. Individual temporal gradients. Mean response rate (in responses per minute) as a function of time since stimulus onset (in seconds) of individual rats under three fixed-interval schedules of reinforcement (FI 30, FI 60, and FI 120 sec).

Temporal Gradients

The asymptotic temporal gradients are the mean response rates of individual rats on Sessions 6–10 as a function of time since stimulus onset (Figure 2). The gradients are plotted separately for the different fixed intervals (30, 60, and 120 sec) for individual rats. The ogive that best fit this response gradient, the thin line near the data points, was calculated on the basis of Equation 1:

$$y = \frac{c}{1 + e^{-(x-a)/b}}. \quad (1)$$

A nonlinear search algorithm that minimized the sum of squares was used for the estimation of parameters a , b , and c , which served as measures of temporal discrimination. This was done with the “nlinfit” function of Matlab (MathWorks, Inc., Natick, MA).

The mean asymptotic temporal gradient across rats in the three fixed-interval conditions is shown in the top panel of Figure 3. The mean response rate, and the slope of the functions, are inversely related to the length of the fixed interval. When these three functions are plotted as relative rate (rate divided by mean rate) as a function of relative time (time divided by time of reinforcement), the three functions superpose, resulting in a “timescale invariance.”

Transition Gradients

The transition gradients are the mean response rate as a function of time since a response criterion. The criterion was set at the time that best separated an initial low rate of responding from a final high rate of responding. The definition of the criterion is specified in the “Time of transition” section. The quantitative analysis of the transition gradients was developed by Schneider (1969).

The asymptotic transition gradients are the mean response rates of individual rats on Sessions 6–10 as a function of time since the time of transition (Figure 4). The gradients are plotted separately for the different fixed intervals (30, 60, and 120 sec) for individual rats. Flat lines are drawn at the mean of the response rate prior to the transition and after the transition. There are small, but systematic, deviations from the break–run pattern of responding.

The mean transition gradient across rats in the three fixed-interval conditions is shown in the top panel of Figure 5. Flat lines are drawn at the mean of the response rate prior to the transition and after the transition. The mean response rate prior to the transition was low and similar for the three conditions; the mean response rate after the transition was high and inversely related to the fixed interval. These functions are replotted as relative rate as a function of relative time in the bottom panel of Figure 5. The relative rate prior to the transition is the rate as a function of time before the transition divided by the mean rate prior to and after the transition; the relative rate after the transition for each condition (FI 30, 60, or 120 sec) is the rate as a function of time after the transition divided by the mean rate prior to and after the transition for the condition. The relative time is the time divided by the time of food availability (30, 60, or 120 sec). On the relative scale, the three

Figure 3. Mean temporal gradients. The mean response rate (in responses per minute) as a function of time since stimulus onset (in seconds, top panel), and the mean relative response rate as a function of relative time since stimulus onset (in seconds, bottom panel).

functions superpose both before and after the point of transition. This is another example of “timescale invariance.”

Indices Based on Temporal Gradients

Figure 6 shows 12 indices of acquisition of temporal discriminations as a function of blocks of 20 cycles of training.

Curvature index. If responses occurred at a constant rate, the cumulative response record would be an approximately straight line from the first response to the final response. The curvature index is a measure of the magnitude of the deviation of a cumulative response record from a straight line. It is the ratio of the area between the straight line and the cumulative record, expressed as a proportion of the total area under the straight line. The area between the straight line and the cumulative record can be readily calculated by numerical integration (Figure 6, panel A). At all the fixed intervals, the curvature index gradually increased in a similar manner from near 0 to near 0.5. The curvature index was developed by Fry, Kelleher, and Cook (1960); a subroutine in FORTRAN was published in *BRMIC* to do the calculations (Maurissen & Inglis, 1978).

Figure 4. Individual transition gradients. Mean response rate (in responses per minute) as a function of time relative to the time of transition (in seconds) of individual rats under three fixed-interval schedules of reinforcement (FI 30, FI 60, and FI 120 sec).

and has been used subsequently in at least 20 articles in *JEAB*, and elsewhere.

Center of best-fitting ogive. Parameter a of Equation 1 is an estimate of the center (the time at which response rate reached half way to its estimated maximum response rate). The center of the ogive gradually increased to about of the 2/3 fixed interval (Figure 6, panel B).

Scale of best-fitting ogive. Parameter b of Equation 1 is an estimate of the scale of the function (a measure of the precision of timing). The scale gradually decreased as a function of the rats' training, indicating an increase in precision related to the fixed interval (Figure 6, panel C).

Indices Based on Time of Transition

Three additional measures were based on response rates relative to a response criterion (Church, Meck, & Gibbon, 1994).

Time of transition. The time of transition (t_1), also called the *breakpoint*, is the time of the response that maximizes the expression in Equation 2, where d_1 is the duration prior to the transition, d_2 is the duration following the transition, r_1 is the response rate prior to the transition, r_2 is the rate following the transition, and r is the overall response rate during the cycle.

$$t_1 = \max (d_1 |r_1 - r| + d_2 |r_2 - r|) \quad (2)$$

Thus, the time of transition (t_1) is the time of the response that maximizes the differences between the absolute differences in initial and final response rates from the mean rate, with each weighted by its duration (Figure 6, panel D). The time of transition was relatively stable, and it was at about 2/3 of the fixed interval.

Mean rate before the transition. The mean rate before the transition was defined as the mean response rates

Figure 5. Mean transition gradients. The mean response rate (in responses per minute) as a function of time since the time of transition (in seconds, top panel), and the mean relative rate as a function of relative time since the time of transition (in seconds, bottom panel).

from stimulus onset to the point of transition, r_2 (Figure 6, panel E). Initially in training, the response rate before the transition increased but then it decreased. It was similar at all fixed intervals.

Mean rate after the breakpoint. The mean rate after the breakpoint was defined as the mean response rate from the point of transition to the end of the stimulus, r_2 (Figure 6, panel F). The response rate after the transition increased in all fixed intervals and was inversely related to the duration of the fixed interval.

Indices Based on Time of Criterion Response

Time of first response (TFR). The time of the first response was defined as the latency from the onset of a stimulus to the first response in a cycle (Figure 6, panel G). The time of the first response increased during training, and it was inversely related to the duration of the fixed interval.

Time of the 25th percentile response (quarter-life). The quarter-life was defined, as the latency from the onset of a stimulus to the time that the first one quarter of responses had occurred, that is, the 25th percentile (Fig-

ure 6, panel H). The quarter-life increased as a function of training, and it was inversely related to the duration of the fixed interval. This measure was described by Herrnstein and Morse (1957); a subroutine in FORTAN was published in *BRMIC* to do the calculations (Maurissen, 1978) and has been the primarily percentile used in articles on fixed-interval behavior in *JEAB* and elsewhere.

Time of the 50th percentile response (TMR). The time of the median response was defined as the latency from the onset of a stimulus to the time of the median response in a cycle, that is, the 50th percentile (Figure 6, panel I). The TMR increased during training, and it was positively related to the duration of the fixed interval.

Indices Based on Response Rates

Mean response rate during the stimulus (Figure 6, panel J). This is a standard measure of response strength. Although it does not provide any information regarding temporal discrimination within a particular fixed-interval condition, it provides information sufficient to discriminate among fixed-interval conditions. As shown in the figure, the stimulus rate was inversely related to the duration of the fixed interval.

Mean response rate during the first 30 sec after stimulus onset. The mean response rate from 0 to 30 sec was defined as the mean response rate from the onset of the stimulus until 30 sec. Because the fixed-interval durations used in the present experiment ranged from 30 to 120 sec, all rats had an equal opportunity to respond in the first 30 sec following stimulus onset on every cycle (Figure 6, panel K). Responding began at about the same rate for all fixed intervals, but the rate increased in the 30-sec FI and decreased in the 60- and 120-sec FIs.

Temporal discrimination ratio (TDR). The temporal discrimination ratio provided a comparison of the response rate at the end of a stimulus with the response rate at the beginning of the stimulus. The measure of response rate at the beginning of an interval was an interval that was 2/15 of the stimulus duration that began at stimulus onset (r_3); the measure of the response rate at the end of the stimulus was an interval that was 2/15 of the stimulus duration that ended at the time that food was available (r_4). The TDR was defined as $r_4/(r_3 + r_4)$, with .5 indicating no temporal discrimination and 1.0 indicating perfect temporal discrimination (Figure 6, panel L). The TDR increased from about .5 to near 1.0 for all fixed-interval conditions.

Summary of results shown in Figure 6. Acquisition of temporal discriminations is characterized by regular changes in performance as a function of training. The 12 panels show the systematic changes in performance for 12 dependent variables. For some dependent variables (such as the curvature index and the temporal discrimination ratio) the acquisition is similar at the three intervals; for some dependent variables (such as the time of the first response and the mean response rate during the stimulus) the functions for the three intervals began at a similar level but then diverged with training; for some dependent vari-

Figure 6. Acquisition of 12 dependent measures of temporal discrimination. The top row shows three measures based on temporal gradients: the curvature index, the center of the best-fitting ogive, and the scale of the best-fitting ogive. The second row shows three measures based on transition gradients: the location of the time of transition, the response rate before the transition, and the response rate after the transition. The third row shows three measures based on the time to a response criterion: the time of the first response (TFR), the quarter-life, and the time of the median response (TMR). The bottom panel shows three measures based on response rates: the mean response rate per minute during the stimulus, the mean response rate per minute during the first 30 sec of the stimulus, and a temporal discrimination ratio (TDR) based on the response rate early and late in an interval.

ables (such as the time of transition and the quarter-life), the functions began and ended at different levels. Conclusions based upon one or two measures of acquisition may not generalize to other measures. A process theory of timing should produce times of responses that simulate the behavior of the animal. This should approximate the results shown for the 12 dependent variables shown in Figure 6 and for any other summary measures of the primary data.

DISCUSSION

Although secondary data analysis is heavily used in many scientific fields, including astronomy, biology, demography, economics, and physics, it is rarely used in experimental psychology. This may be due to the lack of

archived primary data in experimental psychology, or to a social convention that emphasizes the importance of experimental methods including experimental design and data collection (and, historically, apparatus construction). If primary data were preserved, they could be used for new analyses. This would make it possible for more people to be involved in the discovery process, and it would extend the generality of conclusions about principles and theories.

The articles with fixed-interval schedules of reinforcement that were examined reported on average 2.1 measures of temporal discrimination. Thus, the explanations of the behavior may be explanations of only a few dependent variables. Because different summary measures reveal different features of the primary data, explanations of

one summary measure may not explain another summary measure. Ideally, investigators would be able to specify a process model that would produce an output indistinguishable (or nearly indistinguishable) from the primary data (Church, 2001). A process model that produces data similar to the primary data would necessarily produce data that would be similar to any summary measure (Guilhardi & Church, 2004).

Most of the studies used fixed-interval schedules of reinforcement as a convenient baseline to assess the influence of experimental variables. Others have described new summary measures or provided descriptions and explanations of the relationship between the summary measures. These include the relationship between the time of first response and the time of transition (Hanson & Killeen, 1981), the relationship between the analysis of single cycles and single sessions (Baron & Leinenweber, 1994), and the relationship between the response pattern and the response rate (Gollub, 1964). A few studies have described the relationship among five or more measures (Dukich & Lee, 1973; Gentry, Weiss, & Laties, 1983). The Gentry et al. study included an extensive analysis of the relationship between the interresponse time microstructure and the macrostructure of fixed-interval responding.

The availability of primary data from experimental studies of animal learning and performance could have a major impact on the field. These data can be used at any stage of the research process—from guidance in the design of a new experiment to an informed and independent review of evidence. They also make it possible for research contributions to be made by students, scholars, and gifted amateurs interested in behavior but without laboratory facilities. The primary data will be particularly valuable if they are well-documented, peer-reviewed, easily available, in a standard open source form, and supplemented with software tools for analysis and interpretation.

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ARCHIVED MATERIALS

The following materials associated with this article may be accessed through the Psychonomic Society's Norms, Stimuli, and Data archive, <http://www.psychonomic.org/archive/>.

To access these files or links, search the archive for this article using the journal (*Behavior Research Methods, Instruments, & Computers*), the first author's name (Guilhardi), and the publication year (2004).

FILE: Guilhardi-BRMIC-2004.zip.

DESCRIPTION: The compressed archive file contains:

Three read-me files (readme.txt, readme.doc, and readme.pdf). The readme files contain a description of the supplementary material such as content, file formats, file naming conventions, and instructions for use of the data analysis graphical user interface.

One hundred and twenty text files containing the primary data for 10 sessions of each of 12 rats. The primary data are the times (column 1) of events (column 2) that occurred during the experimental session, such as the times of responses, food deliveries, and onset and termination of stimuli.

One Matlab m-file containing the source code of a graphical user interface that can be used in Matlab for exploration or analysis of the primary experimental data.

LINKS: <http://www.brown.edu/Research/Timelab>.

DESCRIPTION: Contains additional data in the same format, documentation of the procedures and formats, and references to publications that analyzed aspects of these additional data.

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