METHODS & DESIGNS

Three-dimensional spatiotemporal imaging of movement patterns: Another step toward analyzing the continuity of behavior

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Computer-aided spatiotemporal imaging techniques, like those that are proving to be important in many other scientific fields, are being used to represent and study movement patterns of animals exposed to basic reinforcement contingencies. Data from a video-tracking system that provides real-time tracking of the position of an experimental animal as it moves about in a three-dimensional space can be plotted in up to three dimensions. When the data are plotted in two spatial dimensions and the time dimension, behavior is captured as continuous patterns or structures in space-time. Spatiotemporal imaging of movement patterns permits regularities to be observed that are not seen as readily in other ways such as watching videotapes of the experimental sessions or simply examining rate of responding. By providing a concise spatiotemporal representation of the movement patterns that occurred in a given experimental preparation, the imaging techniques described here represent an advancement in the scientific study of continuously flowing behavior. Although we concentrate here on movement patterns produced by basic reinforcement contingencies, the spatiotemporal imaging technology is applicable to any research topic in which movement patterns are of interest, such as foraging, place learning, sign language, and limb movement.

Imaging of phenomena in the space-time continuum has become an important means of obtaining insights into the data of many fields in the natural sciences. For example, computer-aided imaging techniques have been used effectively to represent and study the behavior of electrons and other elementary particles (e.g., Schlenker et al., 1979), the structure of crystals (e.g., Amann, Bazley, & Kirchgassner, 1981), the structure of the earth's interior (e.g., Claerbout, 1985), seismic activity (e.g., Berkhout, 1982), the surfaces of distant planets (e.g., Spitzer, 1980), and various biological structures and processes (e.g., Somlyo, 1986). Here we describe a similar technique for imaging the movement patterns of animals under the control of several commonly studied basic reinforcement contingencies (e.g., see Ferster & Skinner, 1957).

Computer-generated data plots of two or three dimensions are not uncommon in psychology. For example, researchers studying basic reinforcement contingencies

have used three-dimensional (3-D) graphics to display distributions of interresponse times (i.e., the times between successive responses such as leverpresses or keypecks) across time (e.g., Gentry, Weiss, & Laties, 1983; Weiss, 1970). In other areas of psychology, 3-D graphics have been used to display electroencephalographic data (Yost, Bremner, & Nasman, 1988), eye-movement data (Latimer, 1988), and data subjected to multivariate statistical analysis (Yost, Gindler, & Bremner, 1988). Unlike the above, however, our focus here is on capturing behavior as continuous patterns or structures in space-time. The importance that spatiotemporal techniques of viewing data can have for investigations of basic reinforcement contingencies is seen by noting that most experiments in this field involve: (1) a *response-defining action* (RDA), such as pressing on a lever or pecking a key to cause a switch to record a response; (2) the *total reinforced behavior* (TRB), such as approaching and activating the lever or key; and (3) *other behavior* (OB), or behavior that is not part of the TRB, such as resting, grooming, preening. In Skinner's (e.g., 1938, 1966) system, the RDA (typically referred to as the *operant*) is treated as a basic unit of behavior. The TRB and OB are dealt with, if at all, by inference from the rate of occurrence of the RDA. However, changes in the rate of the RDA do not indicate whether (1) the amount of time allocated to the OB has changed, (2) the TRB has changed to permit fewer or more instances of the RDA (i.e., fewer

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or more extraneous movements are being made) per unit of time, or (3) the rate of the TRB has changed.

To address such issues, Pear, Rector, and Legris (1982) developed a video-tracking system that provides real-time tracking of the position of a single target animal as it moves about in a 3-D space. The system tracks the highest dark region in the experimental space, which is typically the top of the animal's head. In some cases, the head is painted black to ensure adequate tracking. Data are produced at the rate of 30 samples per second, and are averaged in blocks of three to produce data points at the rate of 10 per second. In our laboratory, the system has been used to study movement patterns of pigeons exposed to various reinforcement contingencies in an operant conditioning chamber (e.g., Eldridge & Pear, 1987; Eldridge, Pear, Torgrud, & Evers, 1988; Pear, 1985; Pear & Eldridge, 1984; Pear & Legris, 1987).

Numerous examples of two-dimensional (2-D) spatiotemporal data plots have been presented (usually of the animal's absolute distance from a reference point, such as the response key or feeder, across time and the path of the animal in the *xy* [i.e., the horizontal] plane) in the research papers published from our laboratory. Recently, however, data obtained with the video-tracking system have been imaged in 3-D, using commercially available software. The imaging process we have developed is illustrated in this article by 2-D spatial plots and corresponding 3-D spatiotemporal plots from data collected in several experiments.

METHOD

Since our concern in this article is with the imaging of the data, only a brief description of the technical aspects of their collection will be given here (for additional details, see Pear et al. [1982] or Pear & Eldridge [1984]). Tracking was done by a unit termed a *video-acquisition module* that analyzed the signals from two black-and-white video cameras observing the target. Discrimination between the target and the background was made on the basis of relative brightness. The cameras were electronically linked so that they scanned the observed scene synchronously at 30 Hz. The video signal from each camera was analyzed line by line from the top of the image, until, having satisfied minimum width and darkness criteria, the target was identified. Logic circuits within the video-acquisition module determined the horizontal and vertical positions of the target relative to each camera. A microcomputer within the video-acquisition module accepted these raw position data and used them to compute the 3-D Cartesian coordinates of the target relative to a predetermined origin. Since the video-acquisition module had limited storage capacity, a second computer was required to acquire, average, and store the data. A Cromemco Z-2D microcomputer was chosen for this purpose because at the time that the system was being built

(the late 1970s) this computer offered superior computing speed and diskette capacity at a relatively low cost. The Cromemco now is outperformed by most personal computer systems; hence, it would not be used for any tracking system developed today. More recently, Poizner, Wooten, and Salot (1986) described a 3-D tracking system that incorporates the IBM PC (see also Jennings & Poizner, 1988). Their system (which is a modified version of a system obtained from United Detector Technology in California) is designed to detect the positions of light-emitting diodes (LEDs) that are attached to the part of the body that is being tracked, and would therefore present a problem for research on organisms that might tend to dislodge the LEDs or obstruct their view from the cameras. Modern systems that detect a target on the basis of brightness contrast or color are available from Cartesian Products Company in Toronto, Ontario, Columbus Instruments in Columbus, Ohio, Coulbourn Instruments in Lehigh Valley, Pennsylvania, and Lyon Electronique International in Lyon, France.

Since the Cromemco has limited data storage capability and the kinds of data analysis programs we required are not available for it, the spatiotemporal imaging of data collected by the Cromemco was done using a Macintosh Plus with an Apple 20MB hard drive. The Cromemco was connected to the modem port of the Macintosh by a standard RS-232 connector and a Macintosh Plus Peripheral Adaptor. A data read-and-transfer program written in FORTRAN was executed, using the Cromemco, while a commercially available communications program, Red Ryder 9.2 (The Freeport Co., 1986), was loaded and executed, using the Macintosh. The data were transferred from the Cromemco to the Macintosh, using full duplex at 4,800 baud, even parity, and 1 stop-bit. Once the desired amount of data was received by the Macintosh, the textfile of data was parsed with a program written in BASIC into the following variables: (1) time, (2) *x*-coordinate, (3) *y*-coordinate, (4) *z*-coordinate (height), and (5) absolute distance of the pigeon's head from an experimenter-designated reference point. Only the first three variables were used in the data plots shown here. Data on each variable were smoothed by a commercially available graphical analysis program, Cricket Graph 1.0 (Cricket Software Inc., 1985). Smoothing was carried out by replacing the third value in each group of five values with the mean of those five values. This technique, which is called a *sliding* or *running average smooth*, enhances the patterns present in the data. The smoothed data were then placed into another commercially available graphical data analysis program, MacSpin Graphical Data Analysis Software 1.1 (D² Software, Inc., 1985), where they were displayed in a 3-D projection on the computer screen. The program permitted the 3-D images to be rotated on the screen in any desired manner.

The data chosen to be presented here had been collected in the course of conducting several different experiments,

Figure 1. Each plot shows 120 sec of data plotted from an *xy* perspective (top view). Each data point is the mean of three coordinate values sampled at the rate of 30 per second. The black circles indicate the position of the response key, feeder, and virtual key, as labeled. The dimensions of the experimental chamber were $57 \times 57 \times 38$ cm. The dashed lines indicate regions of the chamber not visible to both cameras. Data during feeder presentations are not plotted.

and were selected because they exemplified typical results from a variety of experimental preparations.

ILLUSTRATIONS OF SPATIOTEMPORAL IMAGING

Two-Dimensional Spatial Imaging

Figure 1 shows 120-sec samples of data plotted in 2-D in the *xy* (horizontal) spatial dimensions, top view. The top left plot shows data from a pigeon that was exposed to a variable interval (VI) 5-min schedule of reinforcement for keypecking (i.e., reinforcement was delivered following the first keypeck after each of successive intervals varying around a mean of 5 min). The plot indicates that the activity of this bird was concentrated to the right of the key—note the concentration of points in a strip along the front and right walls. The top middle plot shows data from a pigeon that was exposed to a variable time (VT) 5-min schedule of reinforcement (i.e., reinforcement was delivered at a mean rate of once every 5 min, independent of the bird's behavior). This pigeon had previously been exposed to a VI 5-min schedule of reinforcement for keypecking. The plot reveals that the pattern consists of two major elongated parts, or "lobes," that meet at approximately the position of the response key. The top right plot shows data from a pigeon exposed to an

automaintenance procedure in which the key was trans-illuminated with green light 8 sec before the presentation of food that was delivered independently of the bird's behavior. Thus, the green light acted as a conditioned stimulus in a Pavlovian procedure. The key color was red for an average of 60 sec before changing to green. The plot indicates that the bird spent most of the time in a narrow region near the back of the chamber, with occasional excursions to and from the response key. The bottom left plot shows data from an automated shaping procedure (see Pear & Legris, 1987) in which reinforcement was contingent on successive approximations to contacting a computer-defined 3-cm diameter spherical region, termed a *virtual key*, located near the left rear corner of the chamber. Note the concentration of data points—and hence of activity—between the feeder and the virtual key. The bottom middle plot shows data from the same pigeon after shaping had been completed and contacting the virtual key was reinforced on a fixed interval (FI) 15-sec schedule of reinforcement (i.e., reinforcement was delivered following the first contact with the virtual key after 5 min following the previous reinforcement). The plot indicates that this bird's activity was concentrated along a portion of the left wall closest to the virtual key. The bottom right plot shows data from a pigeon exposed to extinction (i.e., no reinforcement) following exposure to a VI 60-sec

schedule of reinforcement for keypecking. Note that no clear pattern was present in the movements, which were concentrated in the part of the chamber nearest to the response key and the feeder. The instance in which the bird appears to have moved toward the back of the chamber was likely spurious, reflecting a tracking error due to the bird's blackened head's not being visible to both video cameras. Such tracking errors are common during procedures such as extinction, when highly erratic movements are occurring.

Two dimensions are suppressed in the above plots: the z (vertical) dimension, and the time dimension. The suppression of the z dimension does not result in the loss of much information, because there was little vertical movement in the above samples of data. However, the time dimension is critical. One way to represent the time dimension is to view the data points plotted sequentially in time, as in watching a movie. For publication purposes, a similar effect is obtained by presenting successive 2-D plots in which the data points cumulate sequentially, so that the movement pattern emerges gradually across the plots (e.g., see Pear, 1985, Figure 3). Another approach is to use 3-D imaging in which time is the third dimension. With this method, movement patterns can be examined as static structures in space-time. This method of spatiotemporal imaging is described in the next section.

Three-Dimensional Spatiotemporal Imaging

Figure 2 shows the data in Figure 1 plotted in 3-D, with time as the third dimension (i.e., the xy plane is extended across time). The plots are *isometric* (i.e., the scale is constant throughout, rather than changing according to the rules of perspective). It is not possible to provide the reader with the full effect of the 3-D imaging technique because these plots are fixed on the printed page. In each plot, however, the orientation chosen for presentation is the one that seems best to display the structure of the data as discovered by rotating the plots on the computer screen. In addition, the scales of the two spatial axes are not necessarily equal but have been chosen to compensate for cases in which greater movement occurred along one axis than the other. The top left plot reveals that the concentration of points in the corresponding plot of Figure 1 represents regular movements along the front and right walls. The top middle plot reveals that the two lobes seen in the corresponding plot in Figure 1 are alternating large and small loops. Note the spiral or coil-like pattern and the regularity of the coils across time. It can be seen from the 3-D plot that the loops to the left of the response key (from the top view) are considerably larger and more regular than the loops to the right of the key. In fact, some of the right loops in the top middle plot are very small. The top right plot in Figure 2 clearly shows the approach to the green

Figure 2. Data from Figure 1 plotted isometrically in 3-D, with time as the third dimension. The data points were smoothed as described in the text, to enhance the movement patterns. The response key, feeder, and virtual key are extended across time, the direction of which is indicated by the arrow next to each plot. The stem of the time arrow indicates 30 sec. The top view of the chamber is extended across time for the sampled behavior of the pigeons on VI 5 min and VT 5 min, while the bottom view is extended across time for the other samples. In each plot, the orientation and the x and y scales, which are not necessarily equal, were selected to provide the clearest view of the movement pattern. The bracketed portions (labeled CS) of the response key in the top right plot indicate periods during which the keylight was green—the color that was paired with food. Data during feeder presentations are not plotted.

keylight (labeled CS) and the withdrawal from the red keylight (i.e., the approach-withdrawal phenomenon characteristic of automaintenance), and regular pacing movements near the back wall when the key was illuminated red. The bottom left plot reveals the occurrence of closer and closer approaches to the virtual key as shaping progressed, as evidenced by the decreasing minimum distance between the points of the graph and the virtual key across time. This plot also shows the bird leaving the feeder area after reinforcement and walking toward the target. (Approaches to the feeder during reinforcement are not shown because the video-tracking system did not collect data during reinforcement.) The bottom middle plot reveals a somewhat irregular search pattern near the target by the same pigeon, after shaping had been completed and the schedule changed to FI 15 sec. This plot also shows the bird leaving the area of the feeder at intervals of 15 sec, corresponding to the delivery of food. Finally, the bottom right plot reveals irregular movements produced by extinction of the keypeck response after reinforcement on a VI 60-sec schedule. Note that during extinction the behavior pattern appears to break down or disintegrate. The tracking error seen in the corresponding plot in Figure 1 can also be seen.

CONCLUSIONS

Spatiotemporal imaging of movement patterns produced by basic reinforcement contingencies permits the viewing of regularities that are not seen as readily in other ways such as viewing videotapes of the experimental sessions or examining event or cumulative records of responding. A videotape contains so much information that it is difficult to extract critical aspects of the behavior from it; in addition, the information is not in an easily recognizable quantitative form. Event and cumulative records of responding omit information regarding the spatial portion of the pattern between successive responses. From a spatiotemporal analysis, an event record of responding is a one-dimensional cross section along the time dimension at the spatial location of the RDA (e.g., the position of the key or virtual key), while a cumulative record is a 2-D cross section along the time dimension and an added dimension consisting of the previous number of RDAs. Although easier to read in some respects, a cumulative record provides no more information than an event record does. As a cross section of the space-time continuum, an event or cumulative record is an incomplete representation of it.

It is apparent from the 3-D plots in Figure 2 that the behavior that is reinforced, or TRB in the terminology used in the introduction, can include considerably more than the RDA. The potential of the technique for displaying OB is perhaps best illustrated in the top right plot in Figure 2, where the behavior of pacing at the rear wall in the presence of the red keylight in the automaintenance experiment can be seen to be distinct from the approach to and withdrawal from the CS. Thus, by providing a con-

cise spatiotemporal representation of the movement patterns that occurred in a given experimental preparation, the imaging techniques described here represent an advancement in the scientific study of continuously flowing behavior.

One of the spatial dimensions was suppressed in the 3-D spatiotemporal plots in this report. As mentioned above, this was not serious, because little movement occurred in that dimension. If imaging across all four dimensions of space-time were desired, it would be necessary to plot one of the dimensions sequentially while viewing the image as a movie.

It is difficult to appreciate the full benefits of spatiotemporal imaging from plots such as those in Figures 1 and 2. The 2-D plots are limited because they lack the time dimension. The 3-D plots are also limited because one cannot rotate any two arbitrary axes on the page around the third axis, as can be done on a computer screen; thus, we do not anticipate replacing 2-D plots with 3-D plots in future publications from our laboratory. However, the 3-D plots are useful in helping develop an intuitive feel for the behavior of an experimental animal and in analyzing the results of experiments. Yost, Bremner, and Nasman (1988) have also described the beneficial effects for the researcher of being able to manipulate 3-D plots and examine them from different orientations.

Thus far, following the conservative scientific approach of testing new instrumentation in an area in which there is a considerable body of knowledge before delving into less explored areas, we have concentrated on basic reinforcement contingencies. Clearly, however, the spatiotemporal imaging technology is applicable to any research topic in which movement patterns are of interest, such as foraging (e.g., Roberts, 1988), place learning (e.g., Cheng, 1988, 1989), sign language (e.g., Jennings & Poizner, 1988; Poizner et al., 1986), and limb movement (e.g., Atkeson & Hollerbach, 1985). Spatiotemporal imaging of movement patterns may also someday have application in the assessment of certain behavioral deficits or disorders in a manner similar to the use of magnetic resonance imaging (e.g., see Foster, 1984) and systems for imaging the internal organs (e.g., MacKay, Potel, & Rubin, 1982) in the diagnosis of medical problems. Such potential future applications, however, are beyond the scope of this article.

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