Laser printers as powerful tools for the scientific visualization of behavior

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Laser printers are powerful tools for the scientific visualization of behavior. Because of their broad software support and their 300 dot per inch resolution, they are not only more cost-effective than plotters and cumulative recorders, but also capable of producing visualizations that would otherwise be impossible.

Laser printers are often viewed as luxury output for word processing. As a result they have been relegated to an inappropriate conceptual niche, when in fact they should be seen as the most cost-effective means of producing visual hard copy in any computer-based research lab. A wide variety of software utilities support postscript or HPGL, which most laser printers also support, and, as a result, laser printers can produce smooth lines at any angle, precisely positioned scatter plots, and shaped characters.

Because of its speed and resolution, and because it is a supported output device, we use our laser printer as a plotter and as a cumulative recorder; we also use it for more traditional purposes, such as poster layout, general-purpose printing, and high-quality page layout. If the laser printer did nothing but save us the cost of a plotter, cumulative recorder, and printer, its purchase would have been justified in terms of its lower net cost. But, most importantly, we also use the laser printer to produce visualizations of data that would be virtually impossible with any other technology.

In animal learning, it is of theoretical relevance to understand the organization of behavior at various levels of temporal molarity and to understand how those levels of organization are systematically related. The accompanying figures present the relationship between behavior and the environment in ways that make it easy for the researcher to understand the organization of interresponse times (IRTs) as a function of time and/or schedule changes, while at the same time retaining the integrity of each individual response. These figures are similar to those presented by Blough (1963) and Weiss (1970), and they illustrate the visualization techniques that have evolved

from the conjunction of our particular research interests, a database of complete inter-event time records (Walter & Palya, 1984), a commercially available application program (PV-Wave), and a laser printer. They are selected to illustrate the capacity of laser printers.

Figure 1 portrays 30,000 responses from a pigeon exposed to a schedule that provides a reinforcer in the context of a constant time since the preceding food presentation (a fixed-interval 60-sec schedule). Time in the interval is denoted across the *x*-axis. The interval starts on the left and progresses to the right as time elapses. The *y*-axis provides for IRTs of up to 3 sec and encompasses most responses. The distribution of IRTs in each portion of the fixed interval and their changes across the interfood interval are clearly portrayed and can be quickly understood. As can be seen, there is a very strong tendency for responses to occur at just less than 0.5-sec intervals. This dominant band of IRTs is relatively constant throughout the interfood interval; it shows that there is virtually no tendency for the bulk of responding to speed up or slow down as the fixed interval elapses. Second, a harmonic can be seen above the main IRT band. This band centers on twice the time of the main IRT. Its temporal relationship to the main IRT band and an analysis of videotape records indicate that it is typically the result of a movement other than an effective keypeck that occurs at the main IRT time. In addition, a band of very short IRTs or "nibbles" can be seen close to the *x*-axis. This visualization provides for the detailed presentation of 30,000 individual responses in such a way that the organization in the behavior is immediately apparent. Both the power typically associated with averaging across large amounts of behavior and the detail of presenting individual responses are available.

Figure 2 illustrates the sequential structure of the responding in Figure 1. It portrays the time of peck $n+1$ as a function of peck n . Each dot portrays the IRT time of peck n by its horizontal position while simultaneously depicting the IRT of peck $n+1$ by its vertical position. As such, it is an n by $n+1$ scatter plot. Again the visualization has both power and detail. As it happens, in this case there is little evidence for any sequential dependency,

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Figure 1. 30,000 interresponse times (IRTs) obtained under a fixed-interval 60-sec schedule. The position of each dot indicates an IRT and the time in the interreinforcement interval when it occurred.

Figure 2. 30,000 pairs of consecutive interresponse times (IRTs) obtained under a fixed-interval 60-sec schedule. The position of each dot indicates the IRT of a peck and the IRT of the peck that followed it.

Figure 3. 8,548 interresponse times (IRTs) obtained under a fixed-interval 60-sec schedule partitioned into 10 discrete periods with a randomly ordered clock. The position of each dot indicates an IRT and the time in the interreinforcement interval when it occurred.

Figure 4. 10,020 interresponse times (IRTs) obtained under a fixed-interval 60-sec schedule partitioned into six discrete periods with a randomly ordered clock. The data from an occasional extended interval is illustrated to the right of the dotted line. The position of each dot indicates an IRT and the time in the interval when it occurred.

Figure 5. 100,000 interresponse times (IRTs) obtained under a variable-interval 60-sec schedule. The position of each dot indicates an IRT and the time in the interreinforcement interval when it occurred.

Figure 6. 30,000 interresponse times (IRTs) obtained under a differential reinforcement of low-rate 20-sec schedule. The position of each dot indicates an IRT and the time in the interreinforcement interval when it occurred.

Figure 7. 30,000 pairs of consecutive interresponse times (IRTs) obtained under a differential reinforcement of low-rate 20-sec schedule. The position of each dot indicates an IRT of a peck and the IRT of the peck that followed it.

in that the clusters simply represent the vertical and horizontal conjunctions of the bands seen in Figure 1 and are proportional to the joint probabilities of those bands. In addition, there is symmetry around the main diagonal.

Figure 3 illustrates responding in a fixed-interval schedule partitioned into 10 periods, each of which was explicitly denoted by a stimulus change. The stimuli were presented in a random order on each trial. The schedule was therefore a fixed-interval schedule with a random clock. The passage of time within the trial is denoted across the x -axis. IRTs of up to 3 sec are provided for on the y -axis. The column of dots at the onset of each stimulus (or "shooters") at the beginning of each stimulus period clearly illustrate the obtained behavior. They are the result of the immediate cessation of responding and a short pause at the onset of each stimulus. This lengthens the IRTs during that period and displaces those dots up the y -axis. The visualization format clearly portrays the dynamics of this particular schedule.

The addition of summary information to a normal "dot plot" is illustrated in Figure 4. This is a peak implementation (Roberts, 1981) of the previous type of procedure. In this case, intervals normally contain six randomly ordered stimuli; however, a random 50% of the intervals do not terminate in food, but rather continue for six more random stimuli, a 3-sec time-out, and then another trial.

The research question concerns the nature of the behavior within each stimulus before and after the normal reinforcement time. The dotted line is used to denote normal reinforcement time, and the histograms summarize the relative rates in each third of each stimulus, while the dots are used to denote the IRT distribution within each stimulus and across the entire interval.

Figure 5 illustrates the degree to which this graphical procedure can maintain the integrity of individual responses while at the same time providing useful summary information. This figure presents 100,000 IRTs obtained under a variable-interval 60-sec schedule. A main IRT band and three harmonics can be seen.

Figure 6 depicts the behavior obtained under a schedule that requires that a pause of at least 20 sec precede a reinforced response (differential reinforcement of low rate or DRL 20-sec schedule). Time since the preceding food presentation is depicted across the x -axis. Because food is frequently not obtained 20 sec after a food presentation, this axis extends well past the minimum of the 20 sec required by the schedule. The y -axis provides for IRTs of up to 30 sec, because that value included most of the responding. The last 30,000 IRTs are presented as a function of time in the interreinforcement interval. This covers responding for approximately 10 months on this schedule, in that DRL rates are so low.

Bird 317: IRT<30.00, 400 Days Date: 11/10/90 (P)

Figure 8. A surface that designates the frequency of occurrence of each of 30,000 pairs of consecutive interresponse times (IRTs) obtained under a differential reinforcement of low-rate 20-sec schedule. The height of the surface designates the frequency of the IRT pairs.

The thin diagonal row of dots in the far left portion of the figure depicts the first peck in each of the inter-reinforcement intervals. For example, an initial response 5 sec into the interval has an inter-event time or IRT of 5 sec, and an initial response 20 sec into the interval has an IRT of 20 sec. The angle of this line is a direct result of the scales used on the x - and y -axes, in that they are both in fact the same time.

All IRTs above the 20-sec mark on the y -axis are followed with food. Therefore, the following IRT starts at the origin with an IRT of 0 sec, and it is 0 sec since food presentation. A response below the 20-sec mark on the y -axis terminates that particular IRT and starts the next IRT interval at the same time since food (same x -axis value). Since it had failed to be reinforced, we simply drop back to the x -axis and again start timing the IRT. As time elapses, the dots are positioned on the same diagonal as that for the initial pecks (specified by the ratio of the x - and y -axis scales). Any responses with IRTs of less than 20 sec are not followed by food and simply reset to the x -axis.

The variance perpendicular to the diagonal (southeast to northwest width) in the first harmonic (20-sec IRTs at 40 sec since food) is mostly attributed to the time of the first peck. The variance can be seen to result from southwest to northeast variation on the diagonal line representing first pecks less than 20 sec, which, in turn, results in east to west variation on the x -axis directly below the points that then, in turn, cause the southeast to northwest variation in the diagonal timing lines for the next IRTs. On the other hand, the southwest to northeast variance of that first harmonic is mostly attributable to the time variation of the second peck, with some variability added by the occurrence of the multiple short IRT pecks, which can be seen along the x -axis.

This process of riding up a diagonal and then resetting to the x -axis and riding up the next diagonal repeats for subsequent harmonics or until food presentation. This format provides a convenient way to understand the dynamics of DRL schedules.

Figures 7 and 8 illustrate the IRT n by $n+1$ scatter plot for the previous DRL 20-sec schedule. Figure 7 provides the data as a dot plot, while Figure 8 provides the same data as a surface. As can be seen, the majority of responses occur with an approximately 20-sec period and are randomly distributed around that point, with little evidence of a sequential pattern. A clear difference between pecks following a food presentation (to the right of 20 sec on the x -axis) and pecks following a prior peck is apparent. The spike in the rightmost position of the figure was added to force the software to scale the figure in the desired way.

In other research programs, of course, other visualizations will be developed. The important idea is to take advantage of the capabilities of a laser printer when one conceptualizes the visualization of data so that the visualizations are as effective as possible in revealing relationships.

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