SESSION XII

CONTRIBUTED PAPERS: PHYSIOLOGICAL/LEARNING ACQUISITION AND CONTROL SYSTEMS

ROBERT M. CHAPMAN, *Eye Research Foundation of Bethesda*, **President**

VRS—A programming system for visual electrophysiological research*

KATHIE D. GOURLAY, WILLIAM R. UTTAL†, and MAUREEN K. POWERS
University of Michigan, Ann Arbor, Michigan 48104

VRS is a system of separate routines programmed to perform one or more of the functions for mapping neuronal receptive fields and determining neuronal response characteristics. The organization and use of the programming system are described along with the details of the routines.

One problem in the study of the visual system has been the accurate mapping of the receptive field characteristics of individual neurons. This report describes a computerized system designed to facilitate studies of neuronal response patterns within the visual pathway. A prominent feature of the system is the automated mapping of receptive fields. The receptive field may be defined as the portion of an animal's total visual field within which appropriate stimuli produce a reliable change in the recorded firing rate of a neuron or a group of neurons recorded simultaneously.

There is a considerable amount of knowledge concerning the internal organization of visual receptive fields, their response characteristics, and their relations to one another (see, for example, Kuffler, 1953; Hubel & Wiesel, 1959, 1962, 1965; Spinelli, 1967; Spinelli & Barrett, 1969; and Barlow & Levick, 1965). In many animals, receptive fields at various levels of the visual pathway are complex, often displaying antagonistic (excitatory-inhibitory) internal organization. These antagonistic fields are sometimes organized in a concentric center-surround arrangement, while in other cases they are organized as adjacent areas, roughly rectangular in shape.

The usual procedure for mapping receptive fields involves the use of a stimulus pattern to explore possible areas of sensitivity in the visual field, and an extracellular microelectrode-tipped system to record the neuronal responses evoked by the stimulus. The recorded responses are analyzed and displayed to demarcate the region of sensitivity. Further experiments

are then carried out to determine responses to different stimulus patterns within the demarcated area.

The laboratory computer is a useful tool for this type of electrophysiological research. Stimulus presentation, response acquisition, and data analysis can be performed simultaneously using an on-line system. Stimulus patterns can be defined precisely and repeated rigorously. Because stimulation can be controlled from the computer console, the E only rarely disturbs the preparation. In addition, data can be collected, analyzed, and displayed very rapidly. The system we describe is designed to take advantage of the computer's abilities.

Ours is not the first computerized system for electrophysiological research. Spinelli (1967), Spinelli and Barrett (1969), and Sasaki, Bear, and Ervin (1971) have used computer systems to study visual receptive fields in the cat. The main asset of the system we will describe is its increased versatility, both in terms of daily experimental operations and of system alterations.

The development of the visual research system (VRS) reported here was motivated by certain specific experimental goals. Psychophysical research indicates that human Ss show high sensitivity to certain geometrical features of dotted visual patterns (Uttal, 1971, 1973). A program of research using the hooded rat as a model preparation was initiated to determine whether there were analogous sensitivities to dotted forms in visual cortex neurons. In the experiments that were planned, a number of characteristics of the stimulus were to be manipulated, including its shape, speed, direction of movement, the number of component dots, the color of the dots, and the orientation of the pattern. Stimulus control was therefore an important part of the system. Receptive fields had to be mapped as a preliminary step in order to determine the appropriate stimulus location within the

*This research was supported by NSF Grant GB25431 and by NIMH Research Scientist Award 5-K05-MH29941-03 to W. R. Uttal.

†Reprint requests should be addressed to W. R. Uttal at 2034 MHRI, University of Michigan, Ann Arbor, Michigan 48104.

Fig. 1. A block diagram of the computer and instrumentation system on which VRS runs.

visual field. Because the differences between stimulated and spontaneous firing rate were often small, it was necessary to add an accumulation or summing procedure capable of pooling several sequential records. Display procedures, including a two-dimensional projection of three-dimensional data, were also programmed.

EQUIPMENT

The visual cortex of the rat's brain was surgically exposed and an etched tungsten microelectrode was driven into the cortex with a hydraulic microdrive in accord with Montero's topographic map of the rat's visual cortex (Montero, Rojas, & Torrealba, 1973).¹ Spike action potentials were amplified and filtered by a Grass P-3 ac coupled preamplifier (c.f. = 1 kHz).

Figure 1 is a diagram of the computer instrumentation system on which VRS runs. The electrophysiological apparatus, the anesthetized animal, and a computer-controlled stimulus oscilloscope were placed within a darkened electrically and acoustically shielded enclosure. The stimulus oscilloscope was under the control of a digital-to-analog converter driven by the computer. It was a point-plotting color unit capable of displaying dotted images on a red, green, or blue phosphor, as selected by the computer program. The stimulus oscilloscope had an 8-in. working area. Stimulus intensities were typically 30-40 cd/m², as measured at the oscilloscope face with an SEI photometer.

The filtered spike action potentials were sent to audio and visual monitors and to a solid state final amplifier.

The final amplifier further amplified the signals and set the dc level to the range required by the analog-to-digital converter (-10 to 0 V). The converter then fed the digitized signal into a PDP-9 computer.

The computer used in this study was a medium-scale installation with 16K words of core storage and both disk and magnetic tape bulk storage. Because control over the exact timing of the various operations was critical, all programming was done in MACRO, the PDP-9 assembly language, rather than a higher level language. The computer program subroutines that measured the neuronal responses recorded only those spike action potentials whose peak amplitudes were above a selected threshold value. As a means of filtering spike-like but lower amplitude noise, only spikes that peaked above a specified minimum amplitude (the THRESHOLD) were accepted. In some instances, we were able to isolate single-cell action potentials, but most records were pooled recordings of the activity of several cells, and thus displayed considerable variation in recorded spike amplitudes. Figure 2 shows a representative recording of spike activity from the rat's visual cortex and illustrates a typical threshold amplitude setting.

Data analysis programs processed the series of detected spike action potentials and were capable of displaying the analyzed results on a line printer, a paper-tape punch, or a data display oscilloscope.

ORGANIZATION AND USE OF THE PROGRAMMING SYSTEM

VRS is a system of separate routines programmed to perform one or more of the functions required for mapping neuronal receptive fields and determining

Fig. 2. A typical recording of unit responses from the rat's visual cortex. The arrow indicates the acceptance threshold for the computer program. Only spikes that exceeded the threshold (downward) are processed further by VRS.

neuronal response characteristics. The component routines are controlled by a set of executive programs which link and load the component routines into a particular experimental sequence. At the present time, six routines are included in the system: (1) CALIB, for stimulus calibration and location within the visual field; (2) RFIELD, for mapping receptive fields; (3) THREED, for displaying data from RFIELD; (4) PLTSPK, for stimulating and recording with respect to receptive field boundaries; (5) HISTO, for analyzing data from PLTSPK and plotting them in histogram formats; and (6) FILES, for storing and retrieving data on magnetic tape.

VRS is open-ended in the sense that new component routines may be easily added. The programmer must only follow a few conventions to insert a new routine into the existing system so that it can be called by the executive programs.

VRS is simple to operate. All communication between the E and the system is done via a control oscilloscope and an associated keyboard. The E controls the order of selection and the starting and stopping times of each routine by means of keyboard commands. Each routine has a set of parameters, which are continuously displayed on the screen of the control oscilloscope after that program has been selected. The E has the option of changing any of these parameters prior to starting the program and still maintain a display of their current status.

Figure 3 is a photograph of a typical command string as it appears on the control oscilloscope. This particular command string directs the executive to call a series of routines (RFIELD, PLTSPK, HISTO) in sequential order. Following the execution of each routine, control is returned to the executive which automatically loads and initializes the next routine called for in the command string, and displays its parameter table.

The E loads the executive portion of VRS, using the

Fig. 3. An example of a command string on the control oscilloscope.

Fig. 4. The parameter table for CALIB.

standard PDP-9 keyboard monitor system loading procedure. From that point on, all routines are loaded by a linking and loading program² within the VRS executive. Typically, the E runs CALIB first in order to adjust the position of the microelectrode within the brain and the stimulus oscilloscope within the animal's field of view. Next, RFIELD is used to map the limits of the receptive field and THREED to plot a two-dimensional projection of the three-dimensional (x,y and the number of responses at x,y) receptive field results on the data display oscilloscope. Characteristics of the neuronal response within the mapped receptive field might then be studied using PLTSPK to examine the effects of particular stimulus patterns at specific locations. The data tables acquired with PLTSPK may then be analyzed with HISTO. Data from RFIELD and PLTSPK may be saved for later reference using FILES.

DETAILS OF THE ROUTINES

CALIB repeatedly displays a single stimulus pattern at any point desired on the face of the stimulus display oscilloscope, so that the position of the stimulus relative to the rat's visual field can be adjusted. It is used to locate the approximate center of a receptive field prior to actual mapping, and as an aid in the location of an appropriate neural response. It is also used for stimulus intensity calibration.

CALIB is capable of displaying any one of a wide variety of moving and stationary patterns. The selection of the particular display pattern is determined by the parameter table shown in Fig. 4. A subroutine, PROTOTYPE, within CALIB, determines the shape of the stimulus pattern. The pattern can be either a straight line or a subset of a 5 by 5 matrix of dots (see Fig. 5). To use the matrix, the parameter table is adjusted appropriately. For example, setting PROTOTYPE equal

Fig. 5. The dot matrix of PROTOTYPE.

to 1 5 7 9 13 produces a pattern of five dots in the shape of a "V." If the pattern is to be a line, the value of PROTOTYPE is set equal to zero. The parameter MOVEMENT is set to 0 if the line is to be stationary and to 1 if it is to move. COLOR defines the stimulus color, and it may be RED, GREEN, BLUE, or NONE. NONE is used to measure the spontaneous activity level of the unstimulated neurons. If the stimulus is a stationary line, ANGDEG determines its orientation. If the line is moving, ANGDEG determines its orientation and direction of movement. If the stimulus is a subset of the 5 by 5 matrix, ANGDEG selects only the direction of movement. CX and CY specify the x and y coordinates of the pattern's position on the stimulus display oscilloscope. NUMBER determines the number of dots in the line, and SPACING determines the distance between dots in the image. NUMBER is relevant only if the image is a line. RANGE is the distance the moving image will travel, and SPEED is its velocity. DENSITY determines the brightness of the image. DELAY is the time in seconds between repeated presentations of the image.

RFIELD, the receptive field mapping routine, displays an identical stimulus sequentially in many different locations within the entire stimulus area (approximately 32 deg of visual angle in our experiments). The relative amount of spike action potential activity evoked at each location defines the limits of the receptive field. RFIELD has the same parameters for determining the stimulus pattern as CALIB and, in addition, several others, as shown in Fig. 6. WIDTH and HEIGHT determine the number of positions in the x and y directions, respectively, of the rectangular plotting array. Stimuli are spaced evenly across the screen, with the distance between the plotting positions determined by the parameter SPACING. PSPACE is used to define the spacing between the dots of the pattern specified with

the parameter PROTOTYPE. The parameters CX and CY, however, have a different meaning in RFIELD than in CALIB. In RFIELD, they denote the x and y coordinates of the center of the rectangular plotting array. START indicates the position of the first stimulus in the rectangular array. DIRECTION allows the E to select the order in which the stimuli are to be plotted: left-to-right, top-to-bottom, right-to-left, or in a random order of presentation determined by a simple algorithm.

At the same time that one subroutine within RFIELD is presenting the stimulus at a given position in the plotting array, another subroutine computes and stores the total number of spikes that occur during and for a specified time following presentation of the stimulus.

RFIELD can be run repeatedly, and the responses from each succeeding run can be summed with the responses of previous runs for each individual position. At the end of each run, the accumulated response data is

```
RFIELD
PROTOTYPE= '0'
PSPACE= 18
START= 'UPPER LEFT'
DIRECTION= 'ACROSS'
DELAY=1
TIME= 1000
SPACING= 50
XCENTER= 512
YCENTER= 512
HEIGHT= 5
WIDTH=5
COLOR= 'GREEN'
THRESHOLD= .600
REPEAT= 1
MOVEMENT=0
```

```
ANGDEG= 180
NUMBER= 5
RANGE=128
DENSITY=4
SPEED=63
OK?
```

Fig. 6. The parameter table of RFIELD (two frames).

written as a numbered file onto the disk. This data is also printed on the high-speed line printer and/or punched on paper tape.

After running RFIELD, the E usually calls THREED to plot a projected two-dimensional display of the three-dimensional results of the receptive field mapping. THREED reads a specified data file from the disk or tape unit that contains the results of any prior RFIELD run and plots a projected drawing of the results on a data display oscilloscope. In this plot, the hidden lines are deleted using a modification of a "hidden line" algorithm by Williamson (1972). Williamson's algorithm has been altered so that both horizontal and vertical lines are simultaneously present in the display. Figure 7 is a photograph of a THREED plot of a typical neuronal cluster receptive field from a rat's visual cortex.

The parameters for THREED that may be modified are shown in Fig. 8. FILE allows the E to select a specific file from disk or magnetic tape for display. The file may be a composite of several runs. PRINT specifies whether or not a duplicate printout or punched paper tape of the original data file will be produced (1 = yes and 0 = no). PLOT specifies whether or not the projected drawing will be plotted on the data display oscilloscope (1 = yes and 0 = no). SWEEPS is a parameter that specifies how many times the picture will be plotted. If one is interested in adjusting the focus or adjusting the oscilloscope gain to scale the figure, SWEEPS is set high enough so that the display is repeatedly regenerated. However, for photographic purposes, it is usually desirable to display the projected drawing only once. ANGLE sets the projection angle of the three-dimensional display to any value between 0 and 90 deg. BORDER (1 = yes and 0 = no) allows the E to add to the drawing a rectangular base and vertical

Fig. 7. A two-dimensional projection of a three-dimensional receptive field as drawn by THREED. The rat appears to have a monophasic field of about 20 deg in extent, with a gradual drop-off in response rate.

Fig. 8. The parameter table of THREED.

border lines such as those shown in Fig. 7. Finally, SLICE allows the E to plot a single two-dimensional cross-sectional slice of the three-dimensional space. Setting the parameter SLICE to V3, for example, would plot the third vertical slice.

Using the information obtained about the shape and extent of the receptive field, the E can carry out detailed examinations of its stimulus selectivity by using PLTSPK. PLTSPK is also a combined stimulus generation and data acquisition program and can produce the same variety of stimulus patterns that are generated by CALIB and RFIELD. However, PLTSPK analyzes the spike responses in much greater detail than does RFIELD. It not only detects the spikes, but measures their amplitude and time of occurrence. These data are formed into tables that are written as numbered files on the disk for future reference by other programs.

Figure 9 is a photograph of the parameter table of PLTSPK.

One especially useful feature of PLTSPK is that the E can set the parameters so that a specified sequence of runs can be automatically repeated a predetermined number of times with different characteristics for each run. The number of times the program is to be repeated is specified by the parameter REPEAT. Parameter values that are to change in each successive run are denoted by assigning them more than one value. For example, if the E were to set:

```
ANGDEG = 0,90,180,270
REPEAT = 4
```

he would systematically test the effect of the orientation of the stimulus on the response and generate four different data tables, each associated with a particular orientation.

Another use of multiple variables is to compare

Fig. 9. The parameter table of PLTSPK (two frames).

stimulated responses to nonstimulated responses. Because the number of responses evoked by each stimulus is small, and because there is always a substantial amount of spontaneous activity occurring in the rat's visual cortical neurons, it is desirable to verify that the differences observed are actually significant by comparing the stimulated values to the unstimulated ones. If the E sets:

```
COLOR = GREEN,NONE
REPEAT = 20
```

he will obtain 20 data files, 10 from stimulated runs and 10 from interspersed nonstimulated runs.

HISTO uses the data from PLTSPK to make both amplitude and poststimulus-time histograms. The data used by HISTO are stored in files on either the disk or magnetic tape. HISTO is also designed to sum the data

from several files and display the accumulated data as one histogram. This accumulation of spike action potentials is directly analogous to the averaging of evoked brain potentials and tends to achieve the same end, namely, to increase the signal-to-noise ratio by enhancing the regularly occurring components of the response and suppressing the random components.

Another feature of HISTO is that it automatically scales itself according to the range of the data values and will use 64 amplitude or time "bins" regardless of the range of the data. If the E wishes to examine a small portion of the total range of values in detail, he can set certain parameters to produce a histogram containing only values that fall within determined limits of either time or amplitude. Figure 10 is a photograph of the parameter table of HISTO. The histogram may be listed on the line printer or punched on paper tape. The total number and standard deviation of the number of spikes in a set of files is output along with the histogram. A sample histogram is shown in Fig. 11.

Finally, we have included within the system a utility program called FILES, which is capable of file manipulation. Data can be transferred from the disk to magnetic tape, and vice versa. The routine was required because of the relatively limited size of the PDP-9 disk.

CONCLUSIONS

Our initial results with VRS generally agree with Montero's measurements of rat visual cortex receptive field size. The more detailed look provided by this system shows the field to be monophasic in shape, with a gradual drop-off from a central peak to the periphery. Both *on* and *off* responses to stimuli anywhere within a receptive field boundary are usually observed independent of stimulus pattern.

By programming VRS, we have developed a powerful and flexible system of programs designed to allow

Fig. 10. The parameter table of HISTO.

```

      AMPLITUDE HISTOGRAM. (311 SPIKES WERE RECORDED)

18  X 3
33
48  XXX 0
63  XX 2
78  XXX 4
93  XX 3
108 XXX 4
123 XXXX 5
138 XXXXX 7
153 XXXXXX 8
168 XXXXXXXXXX 13
183 XXXXXXXXXX/XXXXXX 20
198 XXXXXXXXXX/XXXXXXX 20
213 XXXXXXXXXX 10
228 XXXXXXXXXX 13
243 XXXXXXXXXX/XXXXXXX 24
258 XXXXXXXXXX 10
273 XXXXXXXXXX 14
288 XXXXXXXXXX 14
303 XXXXXXXXXX 14
318 XXXXXXXXXX 14
333 XXXXXXX 8
348 XXXXXXXXXX/XXXXX 15
363 XXXXXXX 7
378 XXXXX 5
393 XXXX 4
408
423 XX 2
438 XX 2
453 XX 2
468
483 XX 2
498
513
528 XXX 3
543 X 1
558 X 1
573 XX 2
588 X 1
603
618
633 X 1
648
663 XX 2
678
693
708 X 1
723 X 1
738
753 X 1
768 XXXX 4
783 XXXXX 5
798 XXXXXX 6
813 XXXXXXXXXX 9
828 XXXXXXXXXX 8
843 XXXX 4
858
873 XXX 3
888 X 1
903 XX 2
918
933 XX 2

      COLOR= 'GREEN'
      ANGDEG=
      CX = 500
      CY = 750
      NUMBER= 5
      SPACING= 24
      RANGE= 128
      SPEED= 63
      ACCURACY= 4
      TIME= 1536
      THRESH= 600
      TABLE= 9
      REPEAT= 10
      DELAY= 3

```

Fig. 11. A sample amplitude histogram output from HISTO.
(It is also possible to produce poststimulus-time histograms.)

precise and repeatable neurophysiological experimentation. Its modular construction and its generality suggest that VRS may also be useful for research in other sensory systems and other animals, as well as in other levels of the visual system.

REFERENCES

- Barlow, H. B., & Levick, W. R. The mechanism of directionally selective units in rabbit's retina. *Journal of Physiology*, 1965, 178, 477-504.
- Hubel, D. H., & Wiesel, T. N. Receptive fields of sign neuron in the cat's striate cortex. *Journal of Physiology*, 1959, 148, 574-591.
- Hubel, D. H., & Wiesel, T. N. Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *Journal of Physiology*, 1962, 160, 106-154.
- Hubel, D. H., & Wiesel, T. N. Receptive fields and functional architecture in two nonstriate visual areas (18 and 19) of the cat. *Journal of Neurophysiology*, 1965, 28, 229-289.
- Kuffler, S. W. Discharge patterns and functional organization of mammalian retina. *Journal of Neurophysiology*, 1953, 16, 37-68.
- Montero, V. M., Rojas, A., & Torrealba, F. Retinotopic organization of striate and prestriate visual cortex in the albino rat. *Brain Research*, 1973, 53, 197-201.
- Sasaki, H., Bear, D. M., & Ervin, F. R. Quantitative characterization of unit response in the visual system. *Experimental Brain Research*, 1971, 13, 239-255.
- Spinelli, D. N. Receptive field organization of ganglion cells in the cat's retina. *Experimental Neurology*, 1967, 19, 291-315.
- Spinelli, D. N., & Barrett, T. W. Visual receptive field organization of single units in the cat's visual cortex. *Experimental Neurology*, 1969, 24, 76-98.
- Uttal, W. R. A masking approach to the problem of form perception. *Perception & Psychophysics*, 1971, 9, 296-298.
- Uttal, W. R. The effect of deviations from linearity on the detection of dotted line patterns. *Vision Research*, 1973, 13, 2155-2163.
- Williamson, H. Hidden-line plotting program. *Communications of the Association for Computing Machinery*, 1972, 15, 100-103.

NOTES

1. We would like to express our thanks to Dr. Montero for sending us a prepublication copy of his cortical map.
2. Some of the programs that were used in the executive portion of VRS were adapted from earlier routines written by Miriam Rogers. Full descriptions of these portions of the executive can be found in *Generative Computer Assisted Instruction in Analytic Geometry*, by William R. Uttal, Miriam Rogers, Ramelle Hieronymus, and Timothy Pasich, Entelek Press, 1972.