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CORNELL AERONAUTICAL LABORATORY, INC.

REPORT NO. VG-1196-G-5

MARK I PERCEPTRON OPERATORS' MANUAL

(Project PARA)

15 February 1960

Contract No. Nonr-2381(00)

B U F F A L O ,   N E W   Y O R K

CORNELL AERONAUTICAL LABORATORY, INC.

BUFFALO 21, NEW YORK
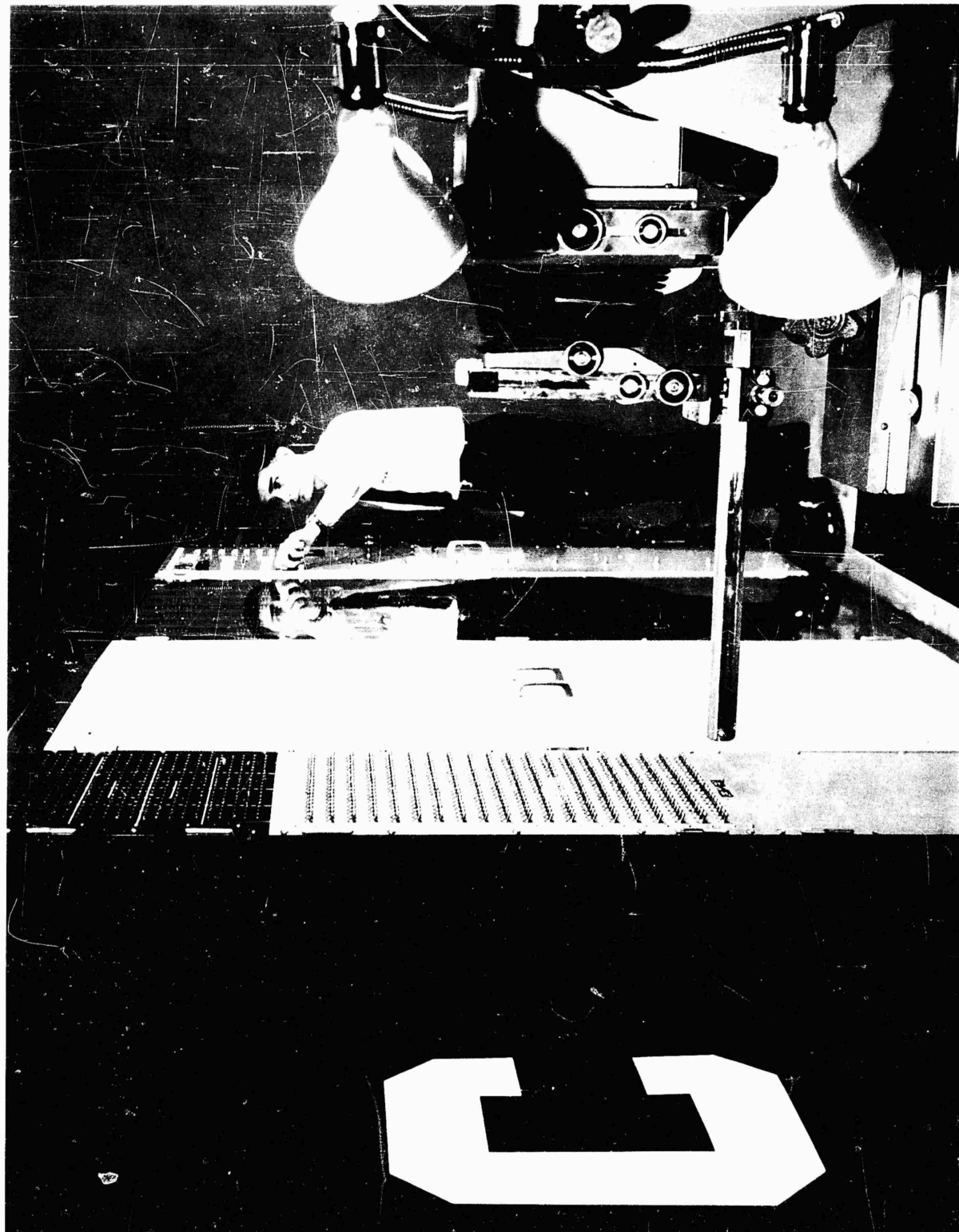
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MARK I PERCEPTRON OPERATORS' MANUAL

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15 February 1960

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TABLE OF CONTENTS

TABLE OF CONTENTS

1. INTRODUCTION

The Mark I Perceptron (Ref. 1, 2, 4) is a pattern learning and recognition device. It can learn to classify plane patterns into groups on the basis of certain geometric similarities and differences (Ref. 4). Among the properties which it may use in its discriminations and generalizations are position in the retinal field of view, geometric form, occurrence frequency, and size.

If, of the many possible bases of classification, a particular one is desired, it can generally be transferred to the perceptron by a forced learning session or by an error correction training process. If left to its own resources the perceptron can still divide up into classes the patterns presented to it, on a classification basis of its own forming (Ref. 5). This formation process is commonly referred to as spontaneous learning.

The Mark I is intended as an experimental tool for the direct study of a limited class of perceptrons. It is sufficiently flexible in configuration and operation to serve as a model for any of a large number of perceptrons possessing a single layer of non-cross-coupled association units.

This manual is intended primarily as a guide to the setting up and operation of the machine. It does not require extensive familiarity with the theory of perceptron systems. For those familiar with the theory, but not necessarily concerned with actually operating the machine, the manual should serve to indicate the machine's potentialities as a research instrument.

Sections 1 and 2 outline the purpose and structure of per-
ceptron systems. Section 3-7 describes how to set up and operate the Mark I.
The Appendix describes the essential mechanisms of the machine; this section
contains information necessary to those who wish to employ experimental
procedures other than the elementary ones of Section 3-7. In particular, the
Appendix tells how to establish connections between the sensory and association
units; such connections are assumed in Section 3-7. Finally the Appendix
describes some apparatus and techniques which have been devised for the
automatic performance of experiments; the use of automatized procedures
should be reserved for the experienced operator.

2. BASIC ORGANIZATION

The sub-units which make up the Mark I machine may be divided into three basic types: Sensory or S-units, Association or A-units, Response or R-units.

Excitation signals are transmitted through the system in the direction from the S-units to the R-units through effectively random connections as shown schematically in Fig. 1.

All the sub-units are of a type which switch on and transmit excitation onward to the next layer only when the sum of their input excitation exceeds a certain threshold. For the Mark I, the input signals of the S-units are in the form of light, while for the rest of the units, the input signals are electrical.

The A-units, however, differ from the others in that when they do switch on, the excitation which they transmit to the R-units has a value which is dependent on the comparative success which that A-unit has had in contributing to the switching of its R-unit in the past. These values form the memory of the perceptron.

A complete view of the Mark I is shown in Figure 2. For a more complete description of the mechanics of the machine the reader is referred to the Appendix.
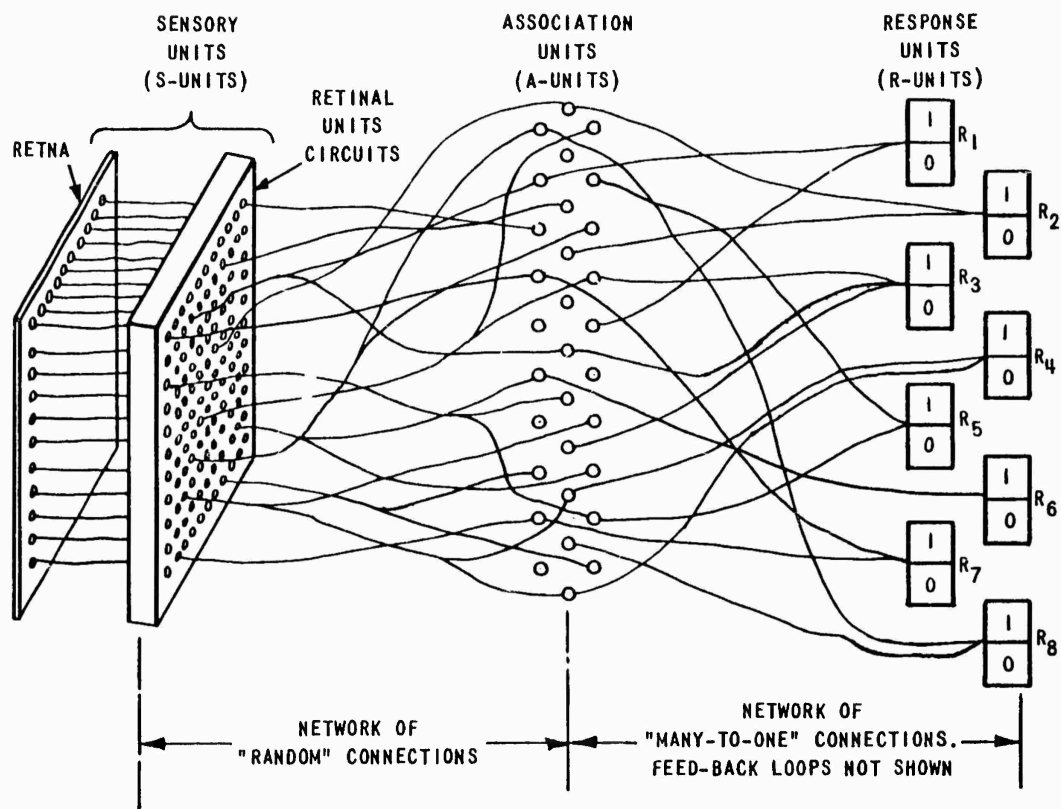
Figure 1 ORGANIZATION OF THE MARK 1 PERCEPTRON

METER PANEL

RESPONSE PANEL

ASSOCIATION UNITS

S-UNIT TO A-UNIT CONNECTION PLUGBOARD

S-UNIT MONITOR

MANUAL STIMULUS SWITCHES

CAMERA

30061
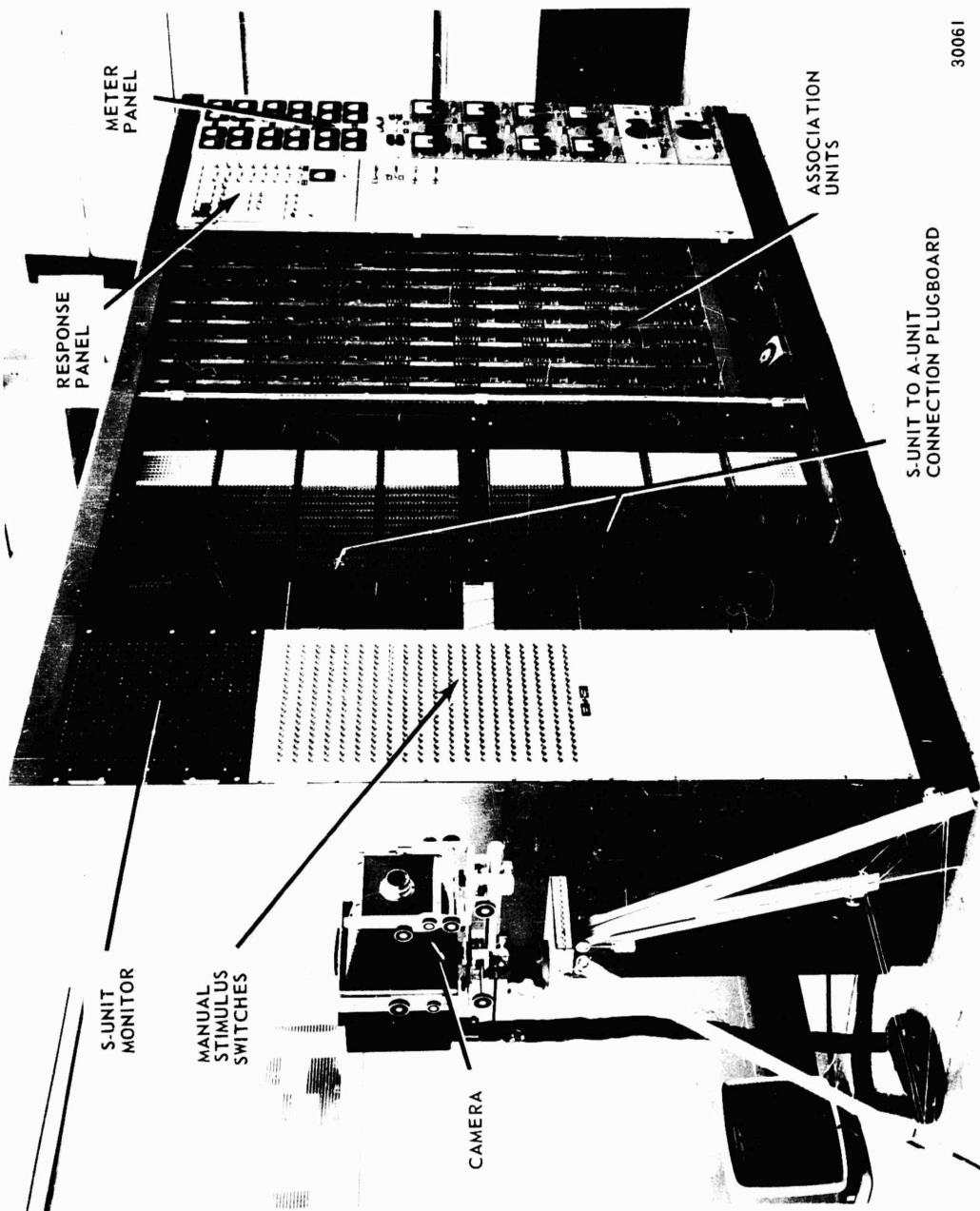
Figure 2   MARK I PERCEPTRON
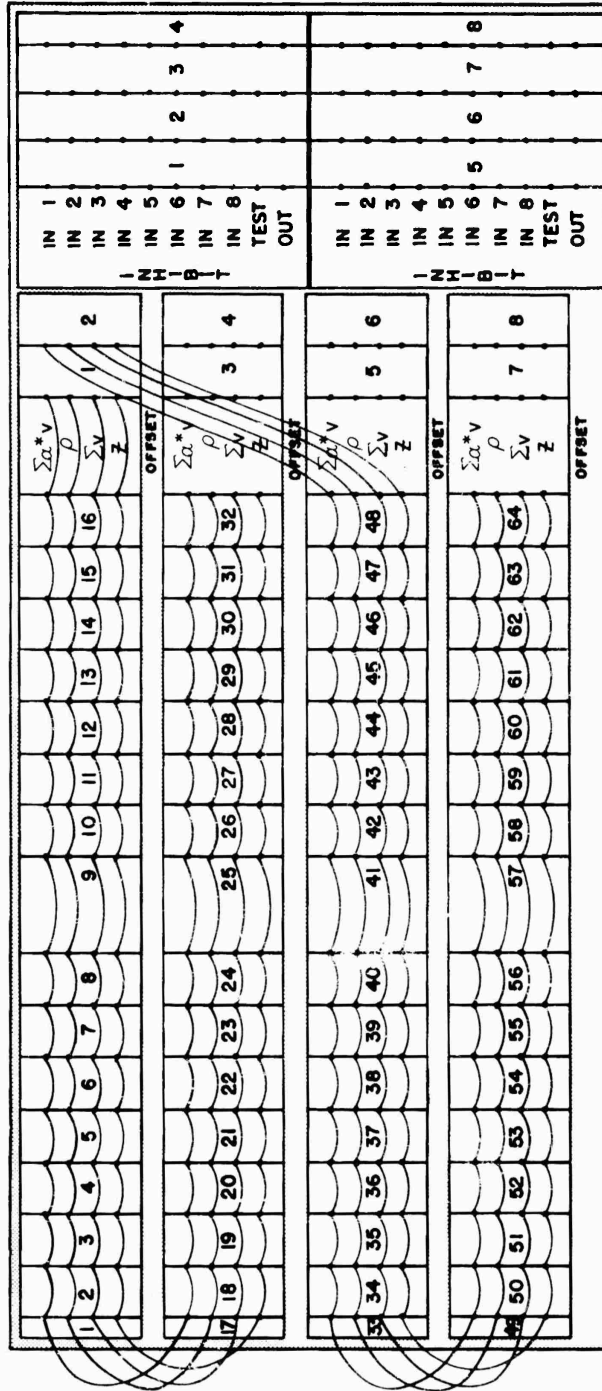
Figure 3   TWO BINARY RESPONSE, NON-EXCLUSIVE

Eg.
FORCED LEARNING SEQUENCE

	R_1	R_2
Square on the left	OFF	OFF
Square on the right	OFF	ON
Circle on the left	ON	OFF
Circle on the right	ON	ON

3. RESPONSE PANEL WIRING

When a classification experiment has been decided upon, the first operation which may be necessary is the rewiring of the response plugboard and this is best done before turning on the power. The board is to be found behind the response panel door.

Three examples of board wiring are given below and from these the wiring for other situations may be deduced.

Example 1

Referring to the diagram of Figure 3, the plug sockets on the left (numbered 1 through 64) are the terminals of the leads from the A-units. Each of these numbers has associated with it four notches which are the output and feedback connection points for 8 ganged A-units; e.g., the notches at number 2 are connected to A-units 9 through 16, the R-unit inputs are situated to the right of center and numbered 1 through 8. Each of these numbers has associated with it 4 input-output terminals in the same relative positions as the A-unit input-output terminals to which they may be connected. It is good practice to wire all the 4 terminal points of each A-unit card to the corresponding points on the destination R-units as shown, including those labelled $\sum'' \nu$ and $\mathcal{Z}$, regardless of whether these will in fact eventually be switched into the circuit or not. (Choice of system will be treated in Section 6).

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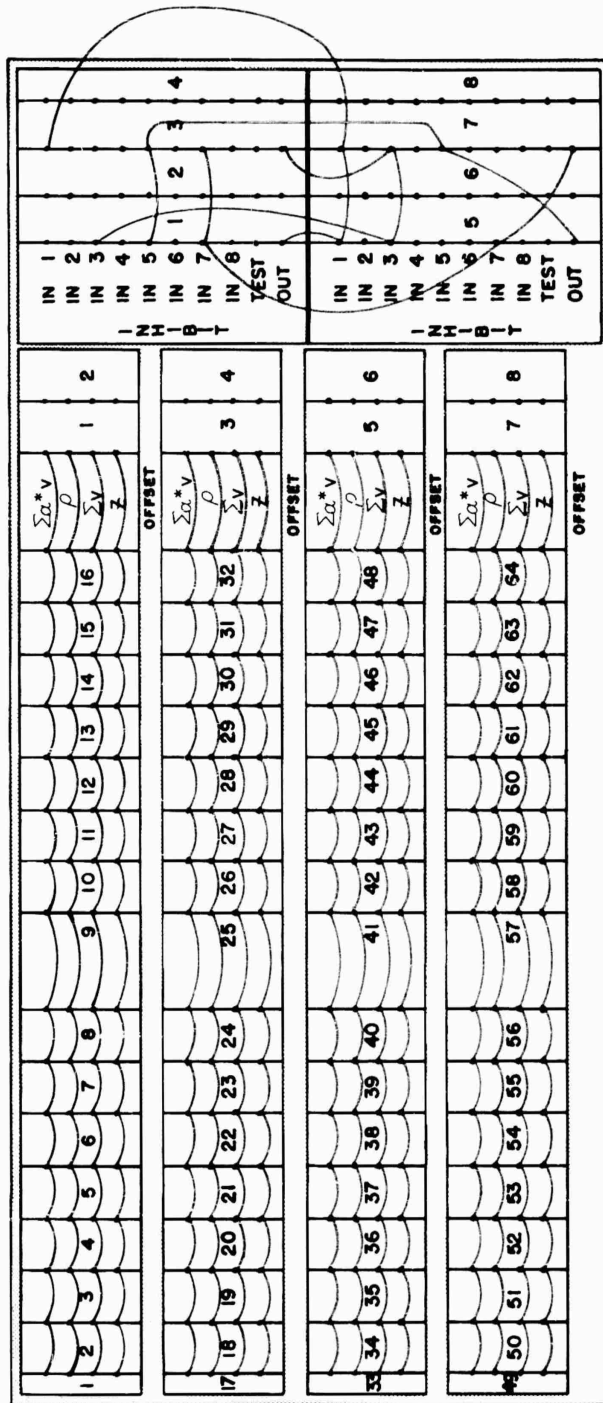Figure 4   FOUR EXCLUSIVE RESPONSES, FORCED LEARNING SEQUENCE

Eg.   E's,   X's,   T's and V's

Example 2

This shows the wiring for a case where four responses are used rather than two. The A-units are divided into four connected subsets rather than two. In this case, also, the responses are mutually exclusive. Mutual exclusion is produced by the illustrated wiring on the Inhibit plugboard at the far right of Figure 4.

Example 3 (Figure 5)

Here is an example of a more complicated wiring for a somewhat more ambitious experiment. Spontaneous discrimination of a number of well-defined classes is desired and advantage is taken of the response wiring scheme described in Tech. Memo No. 2, (Ref. 5), p. 14, in which each R-unit in use is wired to inhibit all others higher than it in number. Briefly, when used in conjunction with memory decay (to be described in Section 6), this connection system allows a single response unit to finally become associated with all the members of a single class even though these members may at the outset be wrongly associated with different R-units. When a sufficient number of members of this class have been displayed to cause the threshold of a lower (numbered) associated response to be exceeded each time, any higher (numbered) response units can no longer turn on and be reinforced. The subsequent decay in their source A-units re-establishes these other response units as candidates for the remaining stimulus classes.

Rewiring can be kept to a minimum if response origin sets are allocated in an orderly manner as in the preceding examples. This will not conflict with randomness requirements since the wiring between the S- and A-units is already random.
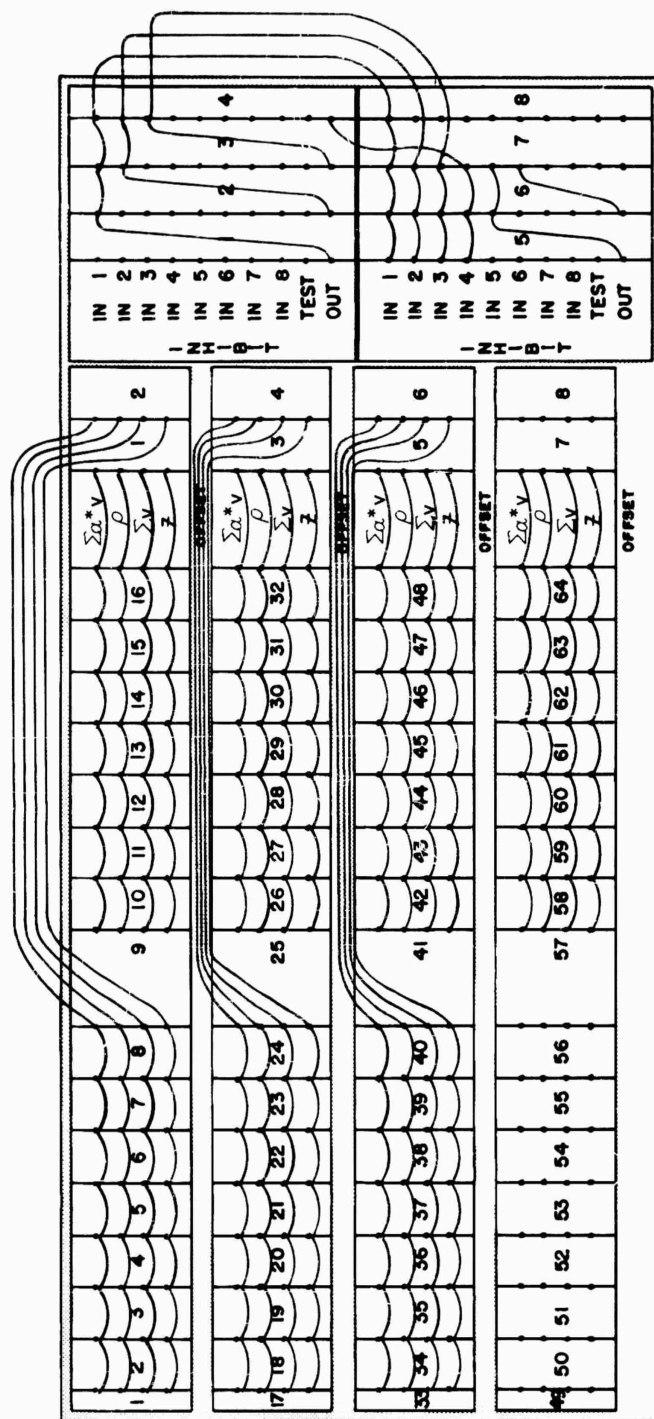
Figure 5   SEVEN EXCLUSIVE RESPONSES - SPONTANEOUS LEARNING

4.   PREPARING MACHINE FOR AN EXPERIMENT

Views of the response unit panel and the meter panel are shown in Figs. 6 and 7. With reference to these diagrams the machine should be started up in the following order.

4.1   Safeguarding Memory from Accidental Modification

Before turning on the power it is good practice to see that the AUTOMATIC/MANUAL switch is on the manual position, and that the CONTINUOUS REINFORCEMENT switch is in the down position. This precaution insures that any memory stored in the A-units will not be accidentally modified. (The fact that the memory system is guarded is indicated, when the perceptron is on, by the illumination of the HOLD VALUE Lamp.)

4.2   Power

The power is turned on by the two switches labelled "400 cps" and "60 cps" in the center of the meter panel. Delays are incorporated so that full operation is not immediately possible.

4.3   Resetting Procedure

Upon the commencement of each new experiment the perceptron will usually need to be reset in order to erase any memory traces left over from previous learning. This procedure can be in progress while the rest of the setting up procedure is being carried out.
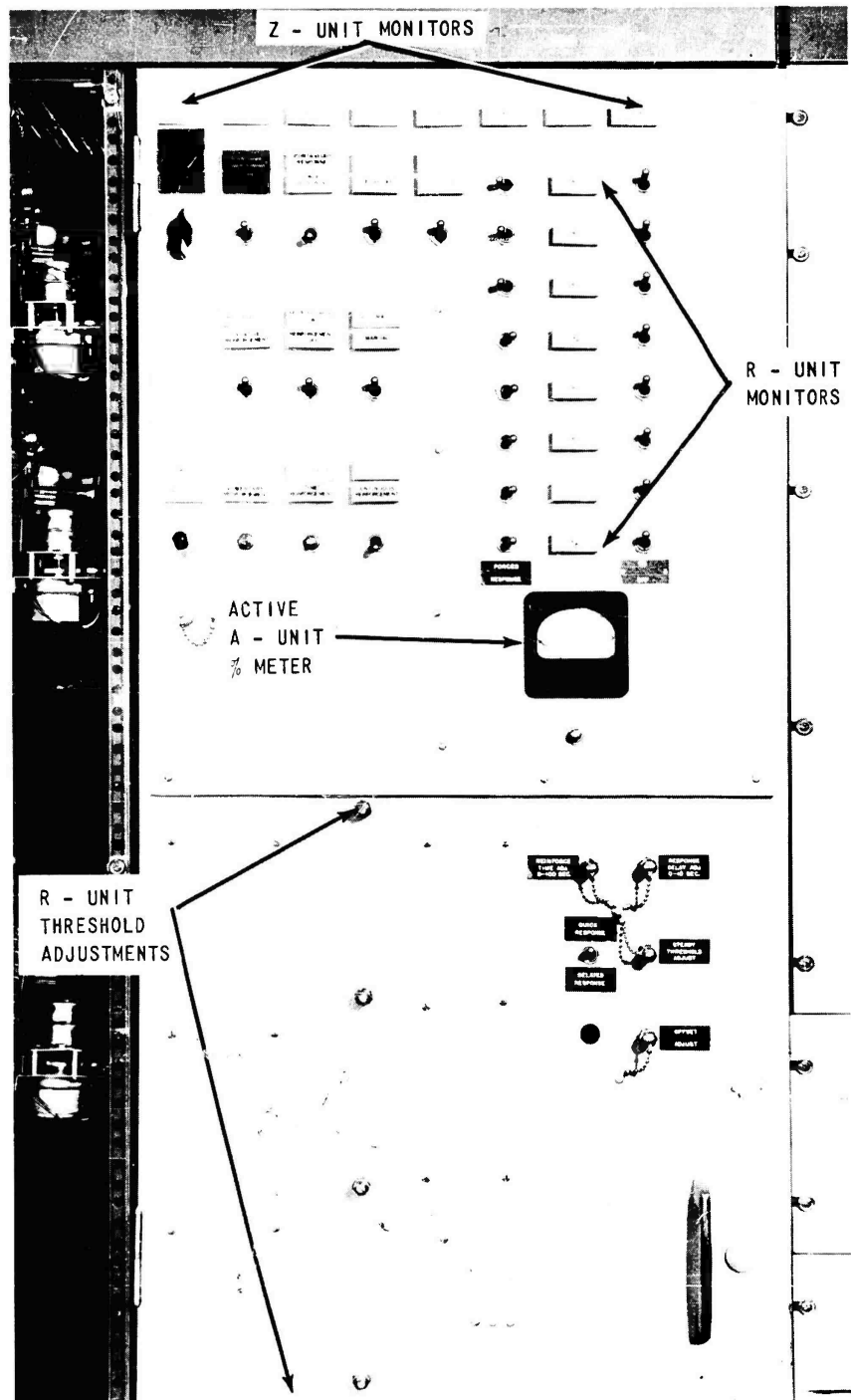
Figure 6   RESPONSE PANEL

The reset switch is situated at the upper left of the response panel, and should be rotated until the RESET 1 label above it is illuminated. When the small D.C. motors of the A-units become inaudible (about 10 minutes should be sufficient), the switch should be rotated clockwise to position 2. After a similar period when the motors have once more become inaudible, the switch should be placed in the RESET 3 position at least for sufficient time for the illuminated Z labels at the top to change over once. (During the RESET 3 operation, it is essential that all R-units to be used in the experiment be turned on.) Normal operation can then be resumed by rotating the switch until the other labels on the panel are illuminated.

4.4 R-Unit Threshold

At the base of the response panel is a screwdriver adjustment for the R-unit thresholds labelled STEADY THRESHOLD ADJUST. For normal operation this should be set and left at its minimum (anti-clockwise limit) where the threshold is a few millivolts positive.

Individual R-unit thresholds can be adjusted by a procedure described in the Appendix (A-4).
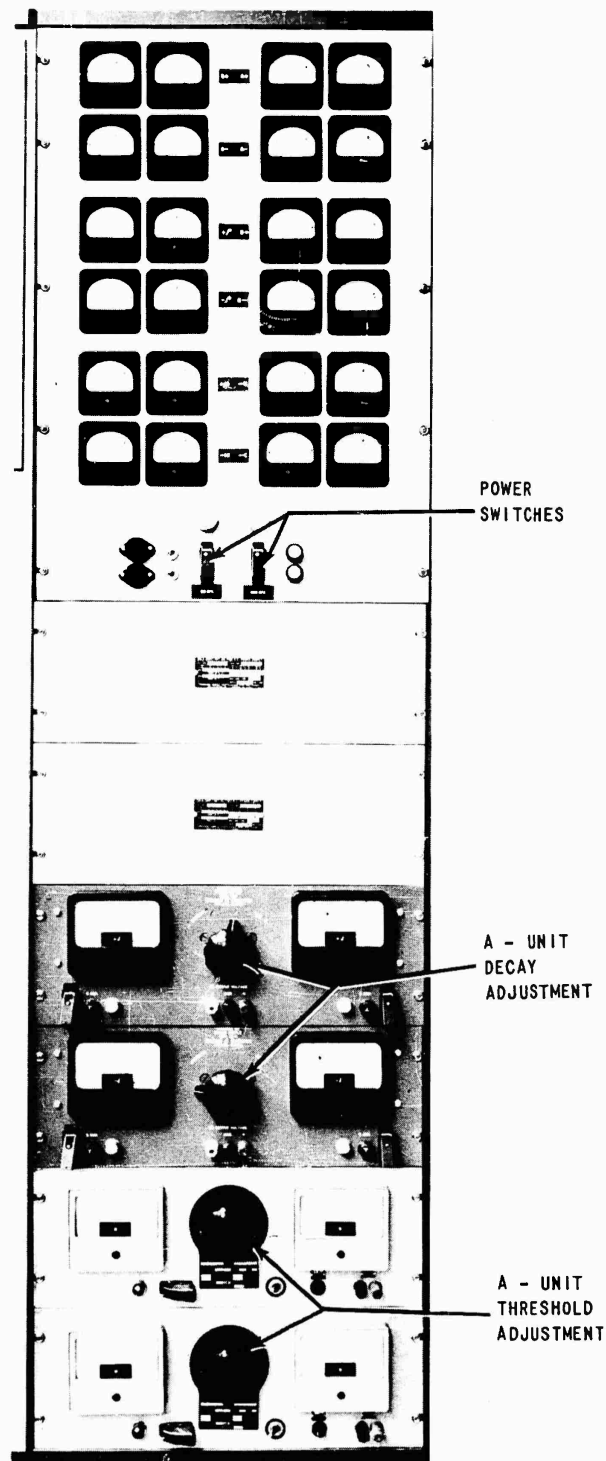
Figure 7   METER PANEL

5.   PRESENTATION OF STIMULUS

After switching on the floodlights, the effect of placing a stimulus should be checked on the S-unit activity monitor before starting an experiment. This is a matrix of neon lamps (see Fig. 2) on which the pattern of activated S-units may be observed. To make this check the SWITCH CONTROL/CAMERA CONTROL switch should be set to the CAMERA position and the protective cap should be removed from the camera lens. If the pattern registered on the monitor is significantly dissimilar to the presented stimulus, the lens aperture or focus may require adjustments.

An alternative method of presenting stimuli is simply to raise the corresponding switches on the array immediately below the monitor. For this, the control switch must be set at SWITCH CONTROL and the cap must be placed on the camera lens. If the photocell bank has been removed from the camera, the cells must be placed face down to prevent light reaching them.

Note that the switching of S-units can have no effect on the memory of the perceptron while the HOLD VALUES indicator is illuminated.

6.   CHOICE OF SYSTEM

There are several perceptron system combinations which may be tested with the Mark I machine. Instructions for setting up each system are listed below in order of increasing complexity.

6.1   The α-System

This is the simplest system and requires a forced learning sequence with equal representation for each class of stimuli.

The use of two switches is required:

(a)   The MONOPOLAR/BIPOLAR REINFORCEMENT switch determines whether A-units are reinforced only when their R-unit is in the "1" position (MONOPOLAR), or whether they are reinforced for both the "1" and "0" positions, but oppositely (BIPOLAR).

(b)   The POSITIVE/NEGATIVE REINFORCEMENT switch which determines the sign of the reinforcement applied when the R-units are in the "1" position.

The Mark I machine is made into an α-system by putting the ZERO ON/OFF switch into the OFF position. It is also necessary, under all ordinary conditions, to put the MONOPOLAR/BIPOLAR switch into the BIPOLAR position.

In forced learning (Section 7.4) with an α-system, the POSITIVE/NEGATIVE REINFORCEMENT switch should be in the POSITIVE position. In using the error correction technique (Section 7.5), this switch should be in the NEGATIVE position.

The use of the DECAY ON/OFF switch is described in Section 6.3. This switch is normally left in the OFF position.

6.2   The γ-System

This system is capable of classification and generalization in a greater variety of forced learning situations that the α-system and in general will be the preferable system to use in such cases. The foregoing α-system is converted to a γ-system by placing the ZERO switch in the "ON" position. This connects the "Zeroing" units, one of which is coupled to each R-unit. Their function is to maintain at zero the algebraic sum of the values of all the A-units connected to each R-unit. During running time (when the HOLD VALUES label is not illuminated) these $\mathbb{Z}$-units will continually cycle back and forth and this activity will be shown on the $\mathbb{Z}$-unit lights at the top of the response unit panel.

With a γ-system set up, the use of the MONOPOLAR/ BIPOLAR REINFORCEMENT switch is no longer restricted since the units will not allow any overall biases to develop. The switch may therefore be placed in either position, though the bipolar system will usually provide faster

learning and should be preferred for that reason. During learning the
POSITIVE/NEGATIVE REINFORCEMENT switch should be at the "POSITIVE"
position and for initial experiments the DECAY switch is best left "OFF".

6.3 Systems with Memory Decay

Some learning experiments may require the use of memory
decay. Any of the above systems may be used for such experiments merely
by changing over the DECAY switch to the "ON" position. When this is done,
the values of all the A-units will decay toward zero exponentially with time
as long as the HOLD VALUE label is not illuminated. The rate of the decay
has an optimum value at which the time required for learning is least[*], and
may be adjusted at the controls labelled " $+ \delta$ " and " $- \delta$ " on the meter
panel. The adjustment should in most cases be made so that the voltages
displayed on the $+ \delta$ voltmeters and the $- \delta$ are left at the same value.
Higher voltages give faster rates of decay and vice versa. The zero voltage
has the same effect as placing the DECAY switch off.

Remarks on other switches remain the same as for the
previous systems.

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[*] F. Rosenblatt, "Perceptron Simulation Experiments", CAL Report
No. VG-1196-G-3, page 31, Ref. 3.

7. LEARNING EXPERIMENTS

7.1   A-Unit Threshold; A-Unit Percentage Meter

One of the experimental parameters is the proportion of
A-units activated by a stimulus. For any given stimulus this may be read
off the A-unit Percentage Meter (Fig. 6). This meter has two ranges con-
trolled by the button beneath it: 0 - 10% or 0 - 100%.

For most experiments, this parameter will be controlled by
assigning a fixed value to the A-unit threshold. This threshold, designated
by θ , may assume any one of the integral values: 1, 2, 3, 4, 5, 6, 7. In
order to establish such a value for the perceptron, the A-UNIT THRESHOLD
ADJUSTMENT is used (Fig. 7).

The THRESHOLD ADJUSTMENT is calibrated in volts, V_θ . To
obtain a given θ , it is only necessary to adjust the voltage V_θ until

$$V_\theta = 24 (\theta - 1) + 3$$

The A-unit THRESHOLD ADJUSTMENT has two alternative
ranges: V_θ = 0 to 50 volts or V_θ = 25 to 100 volts.

7.2   Response State Switches

Each R-unit is a two-state device, having a value of 0 or 1
as indicated by the RESPONSE STATE Lights. Immediately to the left of
each of these eight lights are the RESPONSE STATE Switches. These are

three-position switches: the left position forces the R-unit to the 1 value; the right position forces the R-unit to the 0 value; the middle position forces the R-unit to the 0 value and, in addition, breaks the feedback circuit from that R-unit to the A-units.

The RESPONSE STATE Switches do not control the values of the R-units when the SPONTANEOUS RESPONSE light is on. When this light is on, the R-unit values are controlled by the A-units.

7.3   Testing with the READY/RESPOND Button

Whenever the machine's spontaneous response to a stimulus is to be tested, the READY/RESPOND button is used. For a test, the SPONTANEOUS RESPONSE and MANUAL lights should be on, and the CONTINUOUS REINFORCEMENT switch in the down position. As long as the MANUAL light is on, there is no need to turn off the reinforcement.

The READY/RESPOND lights designate the two basic alternative states of the perceptron. So long as the machine is in the READY state, the A-units are completely isolated from the R-units and any inputs except from the S-units. In the RESPOND state, on the other hand, the A-units send their signals to the R-units, and their memories can be modified.

To test the machine as well as to train it, the machine must be switched to the RESPOND state. This is done by pressing the button just below the READY/RESPOND lights. Pressing the button again will restore the READY state.

Putting the machine into the RESPOND state <u>for a test</u> will cause it to react in one of the following ways:

    (a)   With no inhibitory connections on the response plugboard:

        (i)   QUICK RESPONSE/DELAYED RESPONSE switch set to QUICK RESPONSE - All of the response units whose input exceeds the threshold will be turned to "1" at once.

        (ii)   QUICK/DELAYED RESPONSE switch set to DELAYED - All of the response units whose input exceeds the threshold will be turned to "1" one by one. The first R-unit to respond will be that with the greatest input. The second R-unit to respond will have the next-to-largest input, and so on. Ten seconds should be allowed to elapse after the RESPONSE light is turned on to make sure that all the responses have been made.

    (b)   With inhibitory connections on the response plugboard and the QUICK/DELAYED RESPONSE switch set to DELAYED:

        (i)   The first R-unit to respond will be the one with the greatest input. Any R-unit that this response inhibits will now be held at "0".

R-units not inhibited by this response will become "1" if their input exceeds the threshold.

(ii) It may happen that the first response inhibits no others, but that a later response inhibits the first. In this case, as soon as the latter response becomes "1", the first response changes from "1" to "0".

The perceptron's response should not be tested with the QUICK/DELAYED RESPONSE switch set to QUICK when there are inhibitory connections on the response plugboard. The QUICK RESPONSE does not allow enough time for the proper response sequence to be established.

7.4 Forced Learning

In forced learning the READY/RESPOND button is used to control the establishment of memories in the A-units, rather than to test them.

To begin with, the READY light is on (turned on, if necessary). The switches described in Section 6 are suitably set. Finally, the FORCED RESPONSE, AUTOMATIC, and REINFORCEMENT ON lights are turned on.

This arrangement means that, when the machine is put in the RESPOND state, the values of activated A-units are reinforced according to the rules described in Section 6. In addition, inactive A-units may have their values modified by Zeroing or Decay. This modulation of A-unit values is signified by the illumination of the TIMED REINFORCEMENT light.

The period of value modification will automatically terminate
after an interval determined by the REINFORCEMENT TIME ADJUST on the
lower right of the Response Panel (See Fig. 6). At its counter-clockwise
extreme this control determines an interval of a fraction of a second; it can
be adjusted clockwise up to about 60 seconds. (Note: RESPONSE DELAY
ADJUST should be at its counter-clockwise limit.)

When the perceptron has been thus prepared for a learning
experiment, the training may proceed by repeating the following
FORCED LEARNING CYCLE:

(a)   Present stimulus to S-units.

(b)   Switch response units to "1" or "0" as desired.

(c)   Switch RESPOND light on.

(d)   At end of reinforcement interval, switch
        READY light on.

7.5   The Error Correction Training Technique

A modification of the forced learning procedure can be used
which, in general, leads to better learning. (Ref. 6) In this procedure,
the machine is allowed to spontaneously assign responses to stimuli, and
corrective reinforcement is applied only to those spontaneous responses
which are in error. This modified procedure is thus called the error
correction technique.

For this procedure, the machine is set up as follows:

SPONTANEOUS RESPONSE light on

MANUAL REINFORCEMENT light on

CONTINUOUS REINFORCEMENT light on

BIPOLAR REINFORCEMENT light on

NEGATIVE REINFORCEMENT light on

2 UNITS light off

In addition, the RESPONSE STATE switches should all be turned to the middle or neutral position.

A stimulus is presented and the machine turned to the RESPOND state to test its spontaneous response. The spontaneous response is compared with the required response. Each response unit which has an incorrect value should then have its RESPONSE STATE Switch turned to the left position. (It is actually immaterial which way the switch is turned; the only purpose is to close the reinforcement circuit.)

Negative feedback will now flow to the A-units producing the erroneous responses. In order to check this correcting process, it is necessary to intermittently switch the machine to READY and back to RESPOND. As soon as a response unit has been corrected according to this check, the corresponding RESPONSE STATE Switch should be returned to the neutral position. The frequency with which the correction process is checked will, of course, determine the amount of over-correction which may occur.

The error correction training technique thus consists of repetitions of the following cycle:

ERROR CORRECTION CYCLE:

(a)   Present stimulus to S-units.

(b)   Switch RESPOND light on.

(c)   Observe which R-units give incorrect values.

(d)   Switch the RESPONSE STATE switches left for those R-units giving erroneous values.

(e)   Check progress of correction by switching the machine to READY and back to RESPOND every few seconds.

(f)   When operation (e) shows a response unit to have been corrected, return its RESPONSE STATE switch to the middle or neutral position.

(g)   When all R-units have been corrected, return the machine to the READY state.

7.6   Spontaneous Learning

The spontaneous learning procedure described in Section 6 requires only two modifications of the arrangement employed in forced learning:

Switch the SPONTANEOUS RESPONSE light on,
Turn the RESPONSE DELAY ADJUST to its clockwise limit.

A Spontaneous Learning Cycle consists then, of the following:

(a)   Present stimulus to S-units.

(b)   Switch RESPOND light on.

(c)   At end of reinforcement interval, switch
       READY light on.

7.7 Ordered Procedure for Learning Experiments

This section contains the steps that should be followed when performing a learning experiment on the perceptron. Once the operator is familiar with the preceding sections, these summaries should be used to ensure correct step-by-step operation. Included are references to the sections where detailed explanations of the different operations can be found.

a   FORCED LEARNING

Operation	Section
1. Response Panel wired and relevant R-units turned on......	3.
2. MANUAL and CONTINUOUS REINFORCEMENT switches down (to hold values).................................	4.1
3. Power on...	4.2
4. Reset..	4.3
5. Stimulus presented................................	5.
6. A-unit Threshold set..............................	7.1
7. Response-unit Threshold set by STEADY THRESHOLD ADJUSTMENT.................................	4.4
8. Test initial spontaneous responses (if desired)..........	7.3, 7.4
9. Choice of system: DECAY ON/OFF and ZERO ON/OFF switches set.................................	6.1
10. MONOPOLAR/BIPOLAR REINFORCEMENT and POSITIVE/NEGATIVE REINFORCEMENT switches set.................................	6.1
11. REINFORCE TIME ADJUST set.......................	7.4
12. AUTOMATIC, REINFORCEMENT ON, FORCED RESPONSE lights on	7.4
13. Forced Learning Cycle - This may be repeated as many times as desired, and the stimulus and response can be changed each time..........	7.4
14. Testing: MANUAL, SPONTANEOUS RESPONSE lights on...	7.3

b. THE ERROR CORRECTION TRAINING TECHNIQUE

c.   SPONTANEOUS LEARNING

Operation		Section
1.	Response Panel wired and relevant R-units turned on....	3.
2.	MANUAL and CONTINOUS REINFORCEMENT switches down (to hold values)..........................	4.1
3.	Power on	4.2
4.	Reset..	4.3
5.	Stimulus presented.............................	5.
6.	A-unit Threshold set............................	7.1
7.	Response-unit Threshold set by STEADY THRESHOLD ADJUST..................................	4.4
8.	Test initial spontaneous responses (if desired).........	7.3, 7.4
9.	Choice of System: DECAY ON/OFF and ZERO ON/OFF switches set................................	6.1
10.	MONOPOLAR/BIPOLAR REINFORCEMENT and POSITIVE/NEGATIVE REINFORCEMENT switches set................................	6.1
11.	REINFORCE TIME ADJUST set.....................	7.4(c)
12.	RESPONSE DELAY set (clockwise).................	7.6
13.	AUTOMATIC, REINFORCEMENT ON, AND SPONTANEOUS RESPONSE lights on..........	7.6
14.	Spontaneous Learning Cycle.......................	7.6
15.	Testing: MANUAL light on........................	7.3, 7.6

Steps 14 and 15 are repeated until the test is completed.

APPENDIX - DESCRIPTION OF EQUIPMENT

Section 2 of this Manual contained a very brief description of the connection organization of the Mark I perceptron.   This Appendix will augment that section with a more detailed description of the units themselves and the form of the interconnections.   Some repetition of other material has been allowed for the sake of clarity.

A. 1   Sensors

Each S-unit consists of a photoresistor and some associated circuitry for producing low impedance output signals.   Four hundred photo-resistors are mounted in a 20 x 20 array in the film plane of a modified view camera, while the 400 associated circuits are contained on 40 printed circuit boards mounted vertically like books in five shelves inside the first (left-most) cabinet.

The circuit associated with each photoresistor contains a relay driven by a transistor amplifier whose input signal from the photo-resistor can be adjusted by a potentiometer provided for the purpose of equalizing the output signals from equally illuminated S-points.

When the amplified photo-signal is sufficiently strong to operate the relay. the S-unit produces low impedance +24 and -24 volt outputs.   Otherwise, for all photosignals below this threshold, the out-puts are at zero or ground potential.

At the top of the door to the S-unit cabinet is the 20 x 20 neon lamp monitor array which indicates the condition of the S-unit relays. Below this is a 20 x 20 array of switches which can be used instead of the camera input to simulate arbitrary patterns of activity in the S-units.

A.2 S-units Plugboard

This board, designed to receive miniature plug fittings, provides the means by which any desired set of connections from the S-units to the A-units may be made. Suitable connections are described in Appendix A.10.

A.3 The Association Units

In a similar fashion to the S-units, each A-unit contains a transistor amplifier and a relay. In this case the input excitation is the algebraic sum of all the individual voltages on the connected input lines and the relay will close only if this sum exceeds the A-unit threshold. A single threshold is common to all the A-units and can be varied between 0 and 100 volts by the controls labelled θ at the base of the meter panel. Since the S-unit outputs are all the same 24 volt absolute magnitude, a threshold setting of zero volts will require the number of excitatory inputs to be one in excess of the number of inhibitory inputs in order to fire the A-unit, while a setting of 24 volts will require two extra, and so on. In actual fact, it is convenient (as described in Section 7.1) to always employ
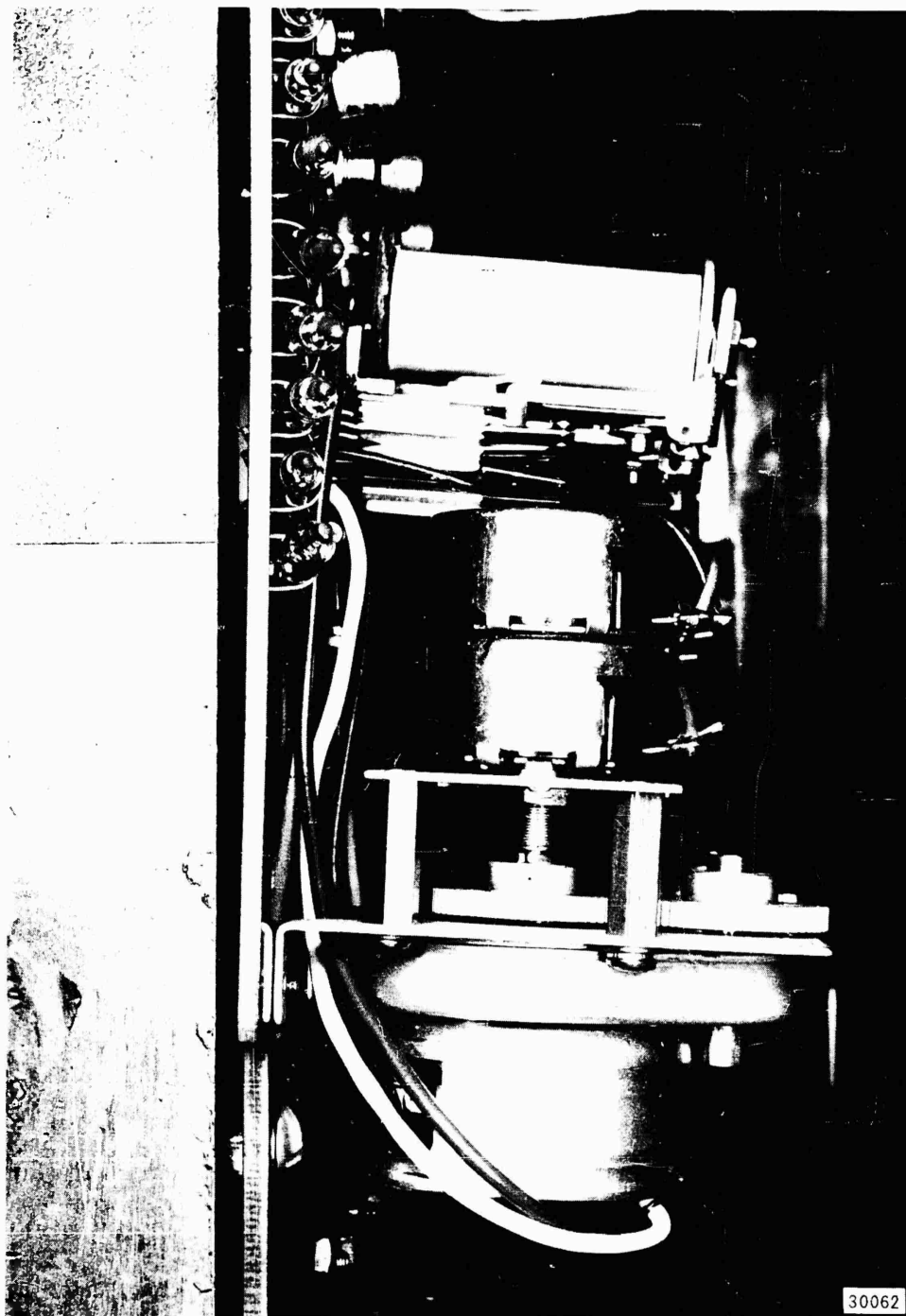
Figure 8   ENLARGED VIEW OF ONE A-UNIT

threshold settings which are 8 volts above this theoretical value, in order to compensate for individual A-unit variations. This is equivalent to setting θ to $\theta + 1/3$, thereby avoiding exact integer values.

The output line leading from an A-unit to an R-unit is energized when the A-unit relay is closed. The voltage on this line, however, is not a constant as is the case for the S-unit, but is a continuous variable whose value may range anywhere between + 11 volts and - 11 volts as a result of feedback from the connected R-unit. This voltage appears at the output of a potentiometer, connected mechanically to a small D.C. motor. The positions taken by the wipers of the potentiometers of all the 512 A-units constitute the memory of the perceptron. The memory is only able to change slowly, the potentiometer shafts turning approximately one-sixteenth of a revolution per minute at the full feedback voltage of 50 volts. However, the effect of its changing may be detected early since the threshold of the R-units may be as low as +5 millivolts.

A close-up photograph of the A-units is shown in Figure 8. Eight A-units are mounted laterally on each printed circuit card. The states of their relays are displayed on the neon lights at the front ends of the cards, the top light responding when the farthermost A-unit relay is closed. An alternative method of measuring the A-unit activity is the meter on the response panel which indicates the percentage activity of the whole set of 512 units.

The output of the second (top) potentiometer on each A-unit can be fed back to its motor to provide a servomechanism loop which will cause the potentiometer output to decay slowly toward zero. This feature may be used to place a limit on the value excursion and is also important for spontaneous learning.

A.4   The Response Units and Zeroing Units

Each of the eight R-units of the Mark I contains a chopper amplifier and a relay. The chopper amplifier of an R-unit has one input from the top terminal (labelled $\Sigma \alpha^* \nu$) of that R-unit's column on the plugboard (see Fig. 9). This input from the A-units is compared by the chopper amplifier to a second input, the R-threshold, which is a parameter of the machine. Only if the A-unit input is greater than the R-threshold does the chopper amplifier close the relay.

The STEADY THRESHOLD ADJUST described in Section 4.4 controls the threshold of all R-units. Each R-unit threshold is, in addition, individually adjustable by use of the eight R-THRESHOLD ADJUSTS, mounted in a column on the lower left of the Response Panel (see Fig. 6). To adjust the threshold of the jth R-unit, turn the jth R-THRESHOLD ADJUST to its counter-clockwise extreme. Make sure, in addition, that the R-unit is on, and the perceptron is in the RESPOND state. The next step is to attach the lead from the R-Calibration Supply, mounted over the Response Plugboard (see Fig. 9), to the $\Sigma \alpha^* \nu$ input of the R-unit. It is also necessary to connect a millvoltmeter (0 - 100 mv) to the jack of the R-Calibration Supply. Now one can apply to the $\Sigma \alpha^* \nu$ input that voltage which is to be the threshold of the R-unit. When this is done, remove the millivoltmeter and turn the appropriate R-THRESHOLD ADJUST slowly clockwise. When the R-unit switches from 0 to 1, the R-THRESHOLD ADJUST has established the desired threshold.

If sc connected on the response plugboard (see Section 4) an R-unit can inhibit its neighbors when its relay pulls in. To avoid possible jitter or oscillation, a lock-up signal is fed back from the output of each R-unit to its own input to keep it in the ON(1) condition once the relay pulls in. This is the reason that in order to obtain a different response the READY/RESPOND switch must be punched to "READY". This puts a large threshold on all R-units, forcing them to the OFF (0) condition. Punching the switch to "RESPOND" allows the threshold to decay slowly, thereby, allowing the R-unit with the largest input to respond first and inhibit others, if such an inhibit arrangement is desired. If the inhibit arrangement is not desired then setting the DELAYED/QUICK RESPONSE switch to "QUICK" disposes of the unwanted delay.

Associated with each R-unit is a zeroing or Z-unit whose function is to keep the sum of values of that R-unit's source set (of A-units) at zero, i.e., when this sum departs from zero because of the reinforcement being fed back from the R-unit, then the Z-unit compensates by incrementing or decrementing all the corrected A-unit values by equal amounts. The Z-unit is similar to the R-unit in construction but has both a positive and negative threshold. When the sum on the Z-unit input rises through the positive threshold the unit changes to the "1" condition and when the sum falls through the negative threshold the unit changes to the "0" condition. The Z-unit achieves its zeroing action by feeding back to the A-unit motors a negative potential when it is in the "1" condition and vice versa. During normal operation therefore, the Z-unit cycles back and forth continually while the HOLD-VALUES label is not illuminated.
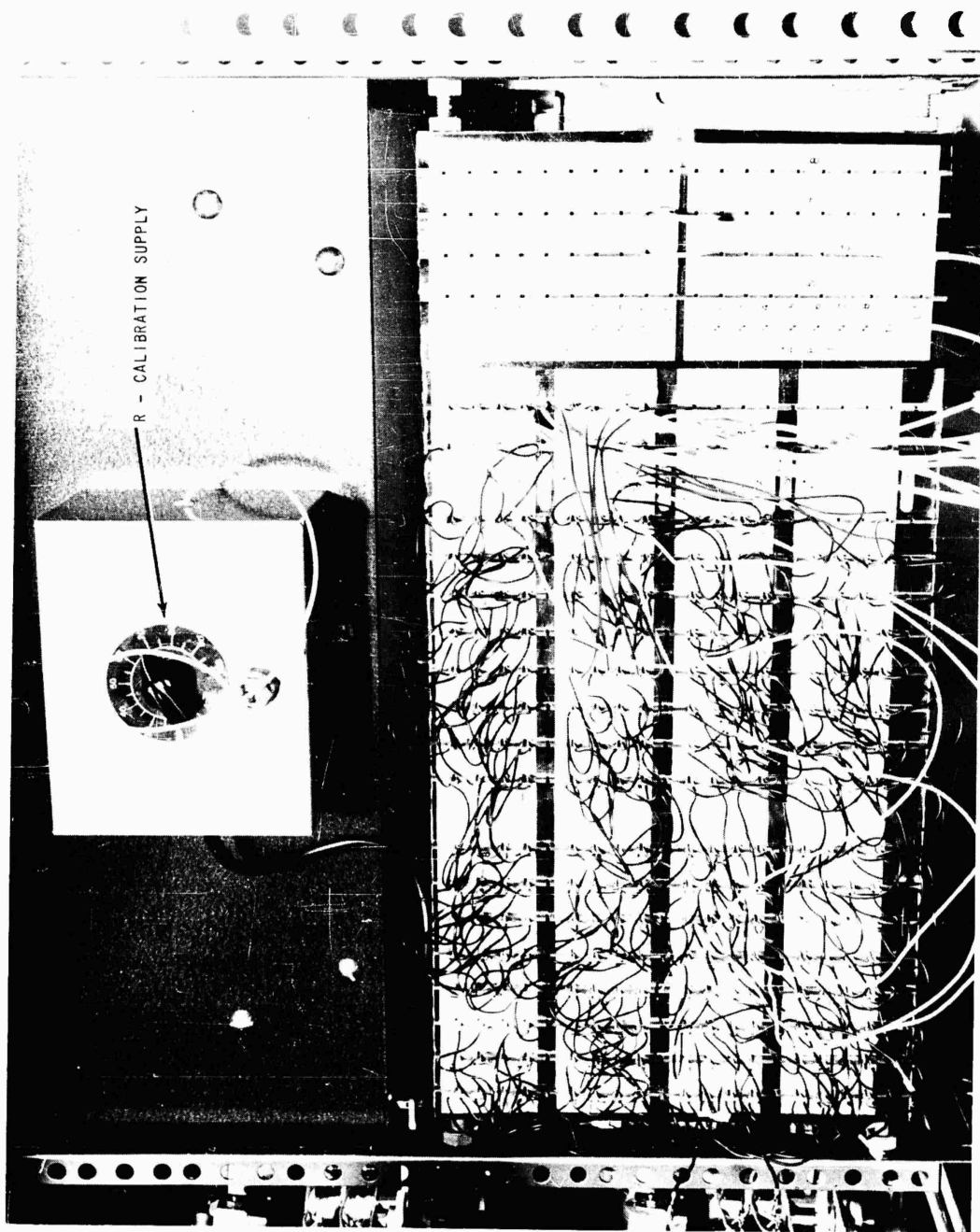
R – CALIBRATION SUPPLY

Figure 9   RESPONSE PLUGBOARD

The $\not{Z}$ -unit OFFSET control can be used to center the
two thresholds about some voltage other than zero. This should remain at
zero unless instability arises as a result of interaction between any R-unit
with its corresponding $\not{Z}$ -unit. Note that the zero voltage is obtained at
the center of the range of adjustment. The value of the OFFSET voltage
may be read from any of the points so labelled on the R-unit plugboard
(ground potential may be taken from the chassis).

Since the reinforcement voltages returned by the R-units are
twice those of the $\not{Z}$ -units in magnitude, the $\not{Z}$ -units may be unable to
maintain the sum of their A-unit source sets at zero if the active proportion
of those source sets exceeds 50%. In such cases the A-unit threshold should
be raised until the active proportion is brought below this percentage.

A.5   Response Unit Plugboard

The response unit plugboard is situated behind the front panel
of the cabinet housing the R - and $\not{Z}$ -units as shown in Figure 9. It
provides the means for a variety of A - to R -unit connection schemes to
suit a variety of learning situations. In order to minimize the complexity
of this board the A -unit outputs have been ganged together in sets of eight,
that being the number of A -units mounted on a single printed circuit card.
The board connection of any such set of eight A -units to an R -unit requires
four parallel lines, labelled $\sum \nu$, $\not{Z}$, $\sum \alpha^* \nu$, and ρ , and whose
purpose is as follows:

The $\sum \alpha^* \nu$ connection carries the sum of the potentials on the "value" potentiometers of all the A-units on that card which are active (i.e., whose relays are closed). It is the sum of those voltages from all the connected A-unit cards which forms the input to an R-unit, and it is this input which must exceed the R-unit threshold for that R-unit to switch on.

The ρ connection carries the reinforcement voltage provided by the R-unit and fed back to the D.C. motors of all the A-units which are active. For a monopolar system this reinforcement line is energized only when the R state is "1", but for a bipolar system a reinforcement (of opposite polarity) is also carried when the R state is "0".

The $\sum \nu$ connection carries the sum of the potentials on the value potentiometers of all the A-units on that card, regardless of whether those A-units are active or not. It is the sum of voltages on all these connected lines which forms the input to the Z-unit.

Finally, the Z connection carries the zeroing voltage which is fed back from the Z-unit to the D.C. motors of all the connected A-units regardless of whether they are active or not. The polarity of the voltage on this line is always such as to drive the A-unit potentiometers in a direction which will eventually switch the Z-unit to the opposite state, so that the Z-units are continually in oscillation in normal operation.

The original design purpose for the $\sum \nu$ and Z connections was to provide a mechanism for a γ-system. One result of this particular design choice is that the R-unit source sets must be disjunct if the $\sum \nu$

and/or Z lines are to be used. Obviously $\sum \nu$ or Z signals of different source sets or different responses cannot be sensibly blended.

A panel which permits inhibit signals to be connected between R-units is physically a part of the response plugboard but is functionally separate. Each R-unit generates an inhibit signal which appears at the notch labelled INHIBIT OUT when that R-unit assumes the ON (1) condition. The several INHIBIT IN terminals also associated with each R-unit are diode isolated, so that each R-unit may be wired to inhibit independently any of the others.

Illustrative examples of wiring for the response plugboard are given in Section 3 of the manual.

A.6   Reading of Actual EMF Values Stored in A-units

In the ordinary operation of Mark I, the individual R-units assign a response of either 0 or 1 to every stimulus because each R-unit has its switching threshold somewhere within the continuous range of EMF values which the A-unit potentiometers can assume.

For analytical purposes, it is sometimes convenient to read these EMF values themselves. I.e., the distribution of such values which a trained perceptron assigns to a set of stimuli contains more information about the results of its training than a simple frequency count of 1's and 0's can provide.

An electronic voltmeter with a suitable selection of ranges is employed for this purpose. This meter is housed in a separate case from the perceptron, with a cable which is plugged in the labelled socket

-41-   VG-1196-G-5

on the R$_e$sponse-unit panel (this socket is directly below that part of the Response-unit panel shown in Fig. 6). On the meter case the following switches will be found:

a.   ON/OFF switch for meter

b.   Eight position switch

c.   Two position switch labeled $\left[\Sigma \alpha^* \nu\right]'$ $\left[\Sigma \nu\right]'$

By positioning switch (b) one can read the values of all the A-units which are attached to a given R-unit. I.e., when switch (b) is at position 5, the meter reads the value of the A-units which are attached to R-unit 5.

The $\left[\Sigma \alpha^* \nu\right]'$ position of switch (c) will ordinarily be employed. In this position, the meter reading is proportional to the total value of all active A-units connected to the given R-unit. The value read on the meter is

$$\left[\Sigma \alpha^* \nu\right]' = \Sigma \alpha^* \nu \Big/ \text{Number of A-units connected to R-unit}$$

In the $\left[\Sigma \nu\right]'$ position switch (c) reads:

$$\left[\Sigma \nu\right]' = \Sigma \nu \Big/ \text{Number of A-units connected to R-unit}$$

$$= \text{Mean value of A-units connected to R-unit}$$

This reading is a useful check on the operation of the $\mathcal{Z}$-units.

A.7 The Reset Switch

The use of this switch was dealt with in Section 3 without an explanation of its action.

For the erasure of any memory trace in the perceptron it is not sufficient merely to cause the A-unit to decay to zero. This is because the D.C. motors have a minimum voltage below which they will not run, so that the residual voltages on the value potentiometers would still agree in sign with the previous memory after such a decay. For this reason the reset procedure commences by forcing all the A-unit values asymptotically to some negative voltage. Only after this are the values allowed to decay towards zero. The reset process is then completed by allowing the Z-units to bring the average value of these residual values to zero, completing the three distinct actions in the operation previously described.

A.8 Additional Reinforcement Controls

The Mark I has two reinforcement controls in addition to those described in Section 7 which increase its flexibility for special purposes.

The MOMENTARY REINFORCEMENT (Fig. 6) push button can be used when the MANUAL light is on. It applies reinforcement only so long as it is depressed.

The push button under the TIMED REINFORCEMENT light is also used with the MANUAL light on. Depressing this button when the perceptron is in the RESPOND state will start the timed reinforcement interval.

VG-1196-G-5

A.9   Automatic Training

Auxiliary equipment has been supplied to facilitate the performance of long experiments with Mark I. This equipment automatizes stimulus presentation, as involved in both forced and spontaneous learning, and response assignment, as involved in forced learning.

Automatic Stimulus Presentations

A 35 mm projector with a motorized slide feed is employed to present stimuli. For this purpose the photo-cell bank is removed from the camera, and mounted on one end of a light-tight box. The projector, at the other end of the box, projects its slides directly onto the retina. This arrangement incidentally provides excellent stimulus-background contrast and minimal background noise; alternatively, a second projector can be added to provide a readily variable degree of contrast and noise.

In using direct retinal illumination of this type, care must be taken not to overburden the photoresistor elements of the retina. The adjustable aperture of the projector should never be set beyond the "2" position. If a second projector is used, further precautions may be necessary.

The stimuli, in the form of 35 mm slides, are inserted into a single (40 slide capacity) or a double (80 slide capacity) tray. Before starting an experiment, it is good practice to check the focus control.

The slides are fed into the projection stage by a signal which can be initiated either by a hand control or, when the projector is set to automatic operation, by an internal timer. When a second signal is given, the first slide is removed and the second slide presented.

For training the perceptron, the timer is set to any value between 4 and 60 seconds. The reliability of the timer is adequate for all ordinary purposes. For testing the perceptron, the hand control of the projector is more suitable.

In a forced learning experiment, the perceptron may be left in the RESPOND state throughout the automatic sequence of slides. In a spontaneous learning experiment, however, a relay is required to switch the perceptron between RESPOND and READY synchronously with the stimulus changes.

Automatic stimulus presentation with this equipment then involves:

(1)   Placing the stimulus patterns in the slide tray.

(2)   Setting the projector's internal timer.

(3)   Preparing the perceptron for forced or spontaneous learning.

(4)   a. Putting the perceptron in the READY state for forced learning or,

        b. Introducing a READY-RESPOND Relay for spontaneous learning.

(5)   Turning the projector to AUTOMATIC Operation.

Automatic Response Assignment

In a forced learning experiment, it is necessary to switch the R-units to the correct binary state for each stimulus. This may be done automatically in conjunction with automatic stimulus presentation.

The method employed is a photo-electric keying of the stimulus slides. It is assumed that the stimuli are such as to never fall on the top row of photoresistors in the retina. This reserved optical space is then used to key the stimuli. Each slide has a hole punched in a particular part of the reserved slide region. This hole causes a point of light to fall on a corresponding element in the top row of the retina. And that photo-sensitive element, in turn, actuates a relay which switches all eight R-units to the desired response state(s).

The requisite precision in keying the slides is afforded by the use of a template and a precision electric drill. The template has ten numbered holes in it, "1", "3", "5" ---- "19" corresponding to the odd-numbered photoresistors of the retina's top row. (The other ten are not used.) Thus up to ten different sets of stimulus slides may be keyed. The template is positioned over a set of up to five slides at a time with two right-angle forms. It is important that, in positioning the slides with reference to the template, the template labels be followed; this insures (a) that the correct position will be drilled, (b) that the drilling is done from the emulsion side of the slides.

To reserve the top row of the retina for this special purpose, it is only necessary to unplug the cables labeled "1^+", "2^+", "1^-", "2^-" at the right rear of the S-unit plugboard. The cables 1^+ and 2^+ are then inserted in the adjacent plugboard labeled "Auto-R Circuit".

When this has been done, the special slide labeled "Master Stimulus Key" should be inserted in the projector, and the projector positioned so that the ten spots of light fall on the ten red-checked photoresistors of the retina. Now it will be noted that the keyed slides activate the corresponding S-units as indicated on the S-unit monitor.

Finally, the small board to the right of the A-unit plugboard labeled "Auto-R" needs to be plugged. On the top half of this board are outlets labeled "1", "3", "5" --- "19" which correspond to the stimulus key positions. On the bottom half of the board are terminals labeled "R1", "R2" --- "R8" corresponding to the eight R-units. Each stimulus key can be wired to any or all of the R-units. All those R-units to which the key is attached will be forced to the "1" state by slides bearing that key; all other R-units will be forced to the "0" state.

At the base of the "Auto-R" plugboard is a switch labeled "ON" and "OFF". This switch activates the "AUTO-R" circuit, and should be on only when it is desired that the keyed responses be forced.

A.10   Sensory-Unit to Association-Unit Connections

Two parameters important in the specification of an S-layer to A-layer connection system are:

1.   The number of excitatory connections, X, to each A-unit.

2.   The number of inhibitory connections, Y, to each A-unit.

The sensory units are connected to two large plugboards, shown in Fig. 2. The top plugboard receives excitatory inputs, and the lower board receives inhibitory inputs. There are 20 electrically isolated plug sockets for each S-unit on each board, making it possible to connect one S-unit to a maximum of 40 A-units.

To the right of the S-unit plugboards are two A-unit plugboards. Each board contains one plug socket for each of the 512 A-units. The top board receives connections from the excitatory S-unit plugboard, while the lower one receives inhibitory connections.

Once the parameters X and Y have been chosen, the wiring could be done in any manner. To eliminate any particular intentional bias in the perceptron, the wiring may be pseudo-random. For this purpose, an IBM 704 program has been written to generate the connections for any set of parameters. The machine prints out, in order, the connections that should be made for each A-unit and the total number of excitatory and inhibitory connections to each S-unit.

Details on the use of the program and the arrangement of the parameter card can be found at the end of this section (A.10) and with the program assembly.

Suggested Procedure for Making S-unit to A-unit Plugboard
Connections

Occasionally the experimenter may wish to alter the S-unit
to A-unit connections. This cannot be done very often, for making the
connections is a costly time-consuming job and, equally important, the
sockets suffer wear every time the connections are changed; even-
tually they may snap off or the conductor may peel off the printed circuit
board.

The notches in the edges of the boards accommodate two
wires. A connection is first made from an A-unit to one of its S-units.
A second wire is attached to the same notch, and then joined to the next
S-unit. This is repeated until all the required S-units are connected to
the A-unit.

Experience in connecting the S-units and A-units has
suggested the following procedures:

1.   The wiring sequence for each set of connections,
        and the placement of each connection, should
        minimize the jamming of the board, and also the
        time involved in plugging those connections. Use-
        ful principles are: (a) The wiring sequence should
        minimize the amount of wire placed on the board.
        (b) Ample wire length should be provided for each
        connection, so that plugged wires are not taut or

or inflexible. (c) The choice of notches for connections to an A-unit should be a compromise between orderliness and convenience, but always with an eye to enabling future connections to be made. If the wiring of the lower S-unit board is begun at the bottom, in the lowest notches, these awkward positions may be filled before they become obscured by the wiring of the easier, upper, notches.

2. It is essential that successive wires of the same set of connections be joined by having been plugged in the same S-unit notch. Similarly, wires of different connection sets must not be plugged to the same S-unit notch or they will not be electrically independent. To avoid mistakes, it is convenient to make the last connection of all sets with the plug socket down, and never to make a fresh connection to a notch which already possesses a down socket.

3. Mistakes may be made in making the connections. As the wiring nears completion, this may result in finding all of an S-unit's sockets filled when the 704 program indicates another connection should be made. In this situation, make the connection to an adjacent socket. The errors should be random, so this will not tend to bias the perceptron.

4. When disassembling connections, care must be taken in pulling out the wires. If the wires are not pulled straight out, the plugs may bend or snap off.

INSTRUCTIONS FOR USING MARK I
PERCEPTRON CONNECTION GENERATION PROGRAM

An IBM 704 program has been written to generate the S-unit to A-unit connections for the Mark I perceptron.

Four parameters of the system and two other numbers must be supplied to the machine. The system parameters are:

1. N_S, the number of S-units to be used (maximum of 400).

2. N_A, the number of A-units to be used (maximum of 512).

3.   X, the number of excitatory connections to each A-unit.

4.   Y, the number of inhibitory connections to each A-unit.

The upper bounds on X and Y are determined as follows: There are 20 x 400 = 8,000 excitatory and 8,000 inhibitory connections possible. The program will not assign the same S-unit twice to an A-unit. The maximum is obtained by dividing 8,000 by the number of A-units to be used and taking the integer part. For example, with 512 A-units

$$\frac{16,000}{512} \quad = \quad 15.6$$

15 is thus the upper bound on X and Y.

The parameter card must be punched in decimal in the first six 4-bit fields. The order is:

Field	Bits	Parameter
1	1-4	Number of association units
2	5-8	X
3	9-12	Y
4	13-16	Initial random number. The connection matrix may be changed by changing this number. "1" has been used in the past.
5	17-20	The range of numbers to be printed in each row of the output. Since there are 100 S-unit plugs in a row on the connection board, this number is usually 100.
6	21-24	Number of sensory units.

The machine will print out in order the connections that should be made for each A-unit, one A-unit to a page. At the end, the total number of excitatory and inhibitory connections to each S-unit is printed.

The program will not use the excitatory or inhibitory connections from any S-unit more than 20 times each. Also, it will not allow any A-unit to be connected to a given S-unit more than once.

With no sense switches set, the output is to the on-line printer, and the Gelac board is used. If sense switch 1 is depressed, the output will be to tape 1. The tape output should be used for any program with more than a few A-units.

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INDEX

A

α-system, 17

A-units (association units), 3, 7, 33, 35, 36, 37, 39, 40, 41, 42, 43, 47-49, 50-53

A-unit percentage meter, 20, 35

A-unit plugboard, 47, 48, 49

A-unit threshold, 3, 20, 28, 29, 30, 33, 35, 39

A-UNIT THRESHOLD ADJUSTMENT, 20, 33, 34

AUTOMATIC/MANUAL switch, 11, 23, 25, 28, 29, 30, 43

Automatic response assignment, 46

Auto-R plugboard, 47

Auto-R switch, 47

Automatic stimulus presentation, 44
    summary of procedure, 45

Automatic training, 2, 44

B

BIPOLAR/MONOPOLAR switch, 17, 25, 28, 29, 30

C

Camera, 15, 31, 44

CAMERA CONTROL/SWITCH CONTROL switch, 15

CONTINUOUS REINFORCEMENT/HOLD VALUES switch, 11, 25

D

Decay, 19, 23, 35

DECAY ON/OFF switch, 18, 19, 28, 29, 30

DELAYED/QUICK RESPONSE switch, 22, 23, 37

INDEX

VG-1196-G-5

INDEX