STABILITY OF VISUAL FIXATION WITH AND WITHOUT FEEDBACK

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The active pursuit of science is not a solitary venture; it is a cooperative effort. This experiment is complete and this dissertation written because many people were willing to give freely of their time, expertise, and concern. Without their assistance, I would have been lost. In particular, I would like to thank Dr. Jack Orbach, who has served as my mentor and who has been my friend. He has always found time to encourage and to guide this work, and for that I am grateful. I am equally grateful for his concern for me as a person.

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Thanks are due to Mr. W. N. Shawnfield of Texas Instruments Inc., who heard that I needed a sensitive, high gain, high frequency photodetector and was kind enough to loan a prototype model to me. Mr. Larry Monari and Dr. Melvin Pavlow each gave much of their time to solve innumerable problems in optics and electronics respectively, and I acknowledge their generous assistance. I acknowledge also the assistance of Dr. Fred Kruger, who was the first person to tackle the design problems with me and who taught me how to use such things as a soldering iron without destroying myself.

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at two or three in the morning. Larry started off as the expert to whom I turned for assistance; he has become my friend and I am richer for it. If dissertations were dedicated, this one would be for him.

To those people that I have inadvertently omitted from this list, I apologize. To my family and my friends who had to put up with crazy hours and unpredictable behavior, for so long, go not only my thanks but also a promise that you shall once again be able to predict my comings and goings. It's been fun and I would do it again - the same way.

A. R. A.

Elmont, New York

May 9, 1972.

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INTRODUCTION

Instructions in a variety of psychophysical, physiological, and perceptual studies (e. g. dark adaptation experiments, retinal locus studies, and perimetry) typically direct the subject (O) to look at a specified target and to maintain the fixation during each trial until exposure of the critical visual stimulus[1] is complete. Implicit in data treatment and analysis is the assumption that O is capable of holding the projection of the center of the fixation spot on the center of the fovea or some other specified retinal point without interruption for the required period (Riggs, Armington, and Ratliff, 1954, p. 315).

The specification of the oculomotor events that follow upon instructions to fixate have infrequently been subjected to experimental scrutiny. That such an examination is called for is suggested by the early data of Guilford and Hackman (1936). They monitored eye position photographically before, during, and after tachistoscopic exposure and found a significant number of deviations from fixation during the fixation interval.

Since that time, a number of investigators (as summarized by Ditchburn and Foley-Fisher, 1967) have measured the magnitude

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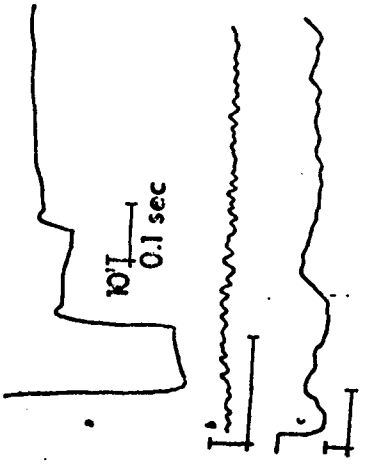
[1]Critical visual stimulus is used to denote a target to be discriminated by O. The term is used to avoid confusion with fixation stimulus, and no special status should be inferred.

of eye movements which occur during monoculus fixation. Three types of movements have been noted: tremor, drift, and micro-saccades. Careful examination of published records reveal instances of single eye movements in excess of 1° during fixation (Figure 1). More commonly however, median saccade amplitudes of 4.5' arc (range 1-50' arc) and median drift amplitudes of 2.5' arc have been reported. These amplitudes reflect the magnitude of individual eye movements during fixation; they are not measures of the magnitude of deviation from the center of the fixation spot. Though each individual eye movement during fixation may be relatively small, the cumulative effect of contiguous movements in the same direction may be large.

Recently, Yarbus (1967) has examined oculomotor events during instructions to fixate a specified point (presumably monocularly). His data were obtained by reflecting a light beam from a suction cap attached to the eye onto stationary photosensitive paper. The cap, like the contact lens used in stabilized image studies (e. g. Ratliff and Riggs, 1950) moved with the eye. Although there is a certain amount of slippage of both contact lenses and suction caps, this slippage is introduced during saccadic jumps which are greater than 5° (Young, 1963). Thus, in Yarbus' record, where there were no saccadic jumps greater than 5°, the record reflected the

Fig. 1. An example of eye movements recorded during monocular fixation. The large deflection in a represents a drift which changed the position of the visual axis by more than 1°. Reprinted from Barlow, H. B.. Journal of Physiology, 1952, 116, 290-306.


10'
0.1 sec

spatial positions viewed by any given retinal element over some period of time. The records showed a large number of drifts; the cumulative effect of these drifts was to move the eye as much as 1-1/2° from fixation during a 60 sec. period under instructions to fixate. Figure 2 (as reproduced from Yarbus, 1967, p. 107) shows that, as the duration of the fixation interval increased, any given retinal element viewed an increasing spatial area. This large cumulative effect of eye movements during fixation may make invalid the assumption that instructed fixation in an uninterrupted event.

Violations of the assumption of continuity of accurate fixation are important (1) because oculomotor activity and visual sensitivity have been shown to be related (Ratliff and Riggs, 1950; Riggs, Ratliff, Cornsweet and Cornsweet, 1953; Volkmann, 1962; Volkmann, Schick, and Riggs, 1968), and (2) because fixation stability is required in those experiments in which retinal locus of the stimulus is specified (e. g. Hecht, Haig, and Wald, 1935).

The relationship between visual sensitivity and oculomotor activity (expressed as the instantaneous acceleration of the image on the retina) is complex, but it probably is best described by an inverted U function (Figure 3). On the one hand, when the retinal effect of eye movements is eliminated through

Fig. 2. The spatial extent of drift eye movements during monocular fixation of a stationary point. Record a shows movements during 10 sec. fixation, record b shows movements during 30 sec. fixation, and record c shows movements during 60 sec. fixation. The area viewed by a single retinal element exceeded 1° in 60 sec.. Reprinted from Yarbus, A. L.. Eye Movements and Vision. New York: Plenum, 1967.

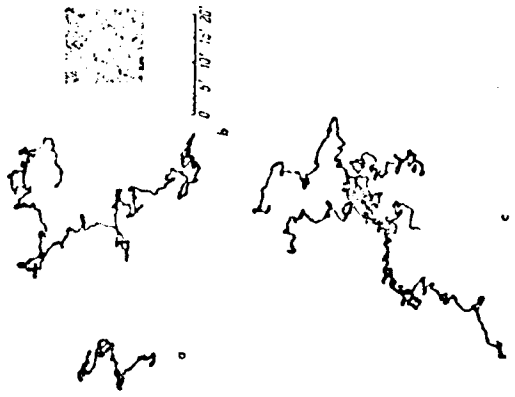
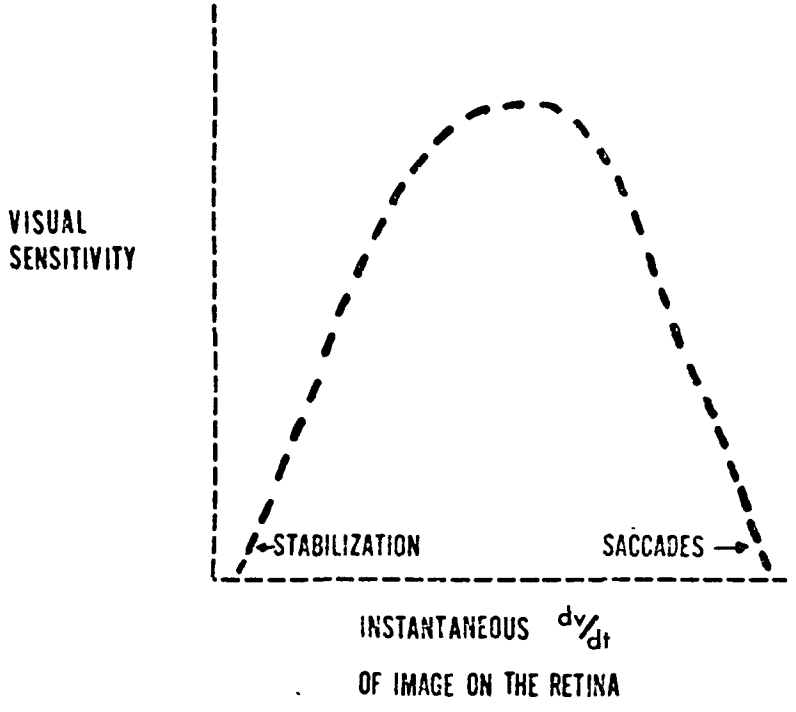


Fig. 3. The hypothetical relationship between oculomotor activity and visual sensitivity. Oculomotor activity is expressed as the instantaneous acceleration of the image on the retina. For a stabilized image, the acceleration of the image on the retina is zero. The shape of the function (normal, skewed) is arbitrary.

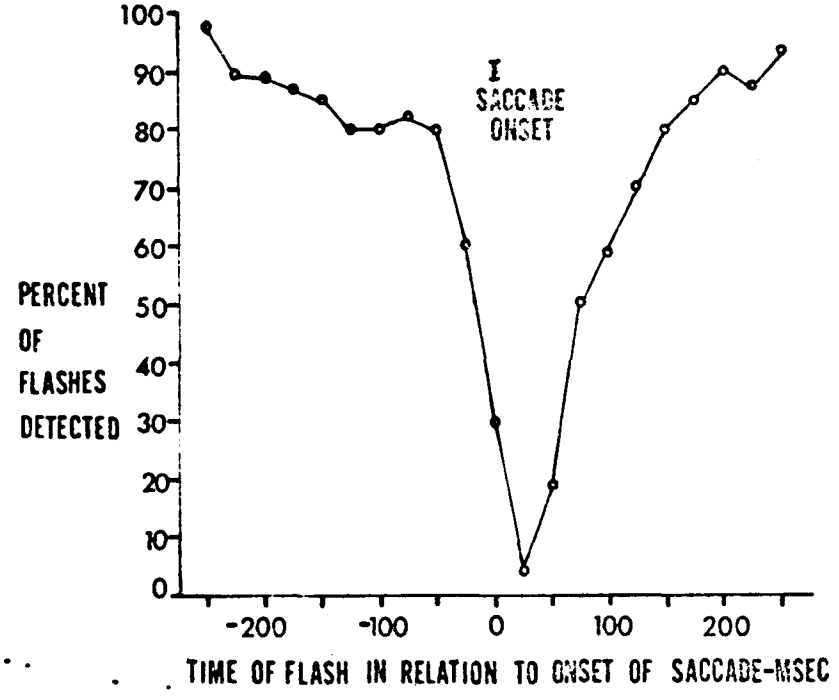

VISUAL
SENSITIVITY
STABILIZATION
SACCADES
INSTANTANEOUS $^{dv}/_{dt}$
OF IMAGE ON THE RETINA

the use of stabilized image technique, visual sensitivity is depressed (Ratliff and Riggs, 1950; Riggs, Ratliff, Cornsweet and Cornsweet, 1953). In these stabilized retinal image studies, the target was reflected onto a plane mirror from a mirror imbedded in a tight-fitting scleral contact lens and then through an optical compensation system onto the retina. The distance from the plane mirror to the eye was exactly twice that from the lens mirror to the plane mirror; thus, the angle through which the target moved on the retina was exactly equal to the angle through which the eye moved. When exposure duration exceeded a few seconds, Os reported that these stabilized retinal images faded. The interpretation that disappearance of stabilized images is related to depression of visual sensitivity is best supported by those studies which showed that modulating the intensity of the stabilized image (e.g. flickering) without moving the image, caused the image to re-appear (Cornsweet, 1956; Ditchburn and Fender, 1955). Hence, changes in the intensity falling on any retinal unit or in the locus of the retinal image seem to aid in preserving visual sensitivity. These changes are brought about by naturally occurring small eye movements and are prevented by stabilization of the retinal image. On the other hand, when the retinal effect of eye movements is preserved and O is instructed to move his eye from

one fixation point to another, (a) changes in intensity on the retina occur rapidly, (b) the retinal image is moved over a relatively great distance, and (c) visual sensitivity is severely depressed. This phenomenon is known as saccadic suppression (Holt, 1903; Latour, 1968; Volkmann, 1962; Volkmann, Schick, and Riggs, 1968; Zuber, Michael, and Stark, 1964).

Volkmann (1962) obtained thresholds for detection of foveally presented dot displays and resolution of foveally presented grating displays both during instructed fixation and instructed saccades. Thresholds during saccades were found to be one-half log unit higher than thresholds during fixation. Volkmann et. al. (1968) varied the interval between the onset of a signal to execute a saccade and the onset of a target. O indicated, for each instructed saccade, whether or not the target had been presented. Post session analysis of film records showing both eye position and the target superimposed on the eye position, revealed the precise temporal relationship between the beginning of the saccade and the onset of the target. Percent of flashes detected was expressed as a function of the interval between onset of target and saccade. The time course of saccadic suppression thus obtained is shown in Figure 4. Using a criterion of 50% visual sensitivity, the decrease in visual sensitivity preceeded the onset of the saccade by 30 msec. and extended at least 100 msec. beyond the beginning

Fig. 4. The time course of saccadic suppression. Averaged data from three Os. Redrawn from Volkmann, Schick, and Riggs. Journal of the Optical Society of America, 1968, 58, 562-569.


100
90
80
70
60
50
40
30
20
10
0
PERCENT OF FLASHES DETECTED
SACCADE ONSET
-200
-100
0
100
200
TIME OF FLASH IN RELATION TO ONSET OF SACCADE-MSEC

of the saccade. Thus execution of undetected saccades during the fixation interval may artificially raise threshold measures obtained in psychophysical investigations. How much thresholds will be raised depends on the temporal relationship between the onset of stimulation and the beginning of saccades which either preceed or follow stimulus presentation.

In summary, both stabilization and saccadic movement depress visual sensitivity. The proposed relationship between oculomotor activity and visual sensitivity was shown in Figure 3, where oculomotor activity is expressed in terms of acceleration of the image on the retina. That visual sensitivity is a function of acceleration and not velocity is suggested by the observation that constant velocity eye movements (e.g. tracking) do not result in suppression of visual sensitivity. It appears that stabilization depresses visual sensitivity by decreasing the rate of change in position of the image on the retina to zero, whereas saccadic movements presumably depress sensitivity both by increasing rate of change to a level so high that the visual system momentarily is unable to process the incoming information, and by simultaneously signalling the system (more centrally) that the eye is moving. Thus visual sensitivity appears to be influenced by rate of change, and it is bounded on both extremes. Evidence to support this point of view is provided by Enroth-Cugell and Jones (1963). They recorded

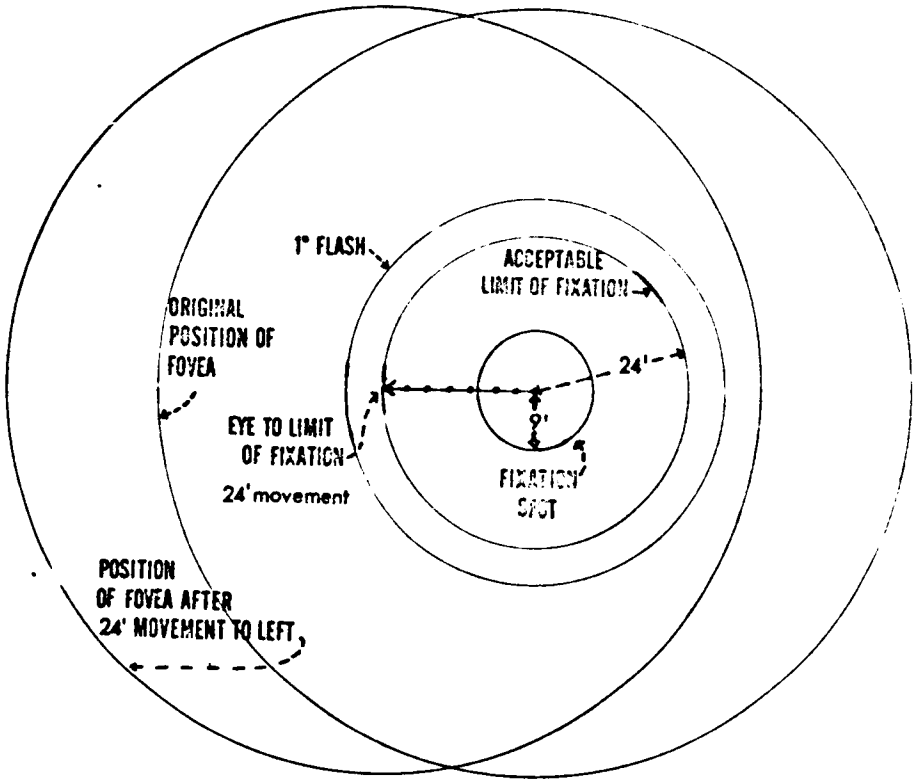
extra-cellularly from cat retinal ganglion cells while varying the rate of change of the stimulus intensity. "In some units the impulse frequency of the response was maximal for intermediate rates of change of stimulus intensity and essentially no change in frequency occurred for faster or slower ramps. This was observed both at on and at off" (Enroth-Cugell and Jones, 1963, p. 907). This evidence leads to the suggestion that studies involving measures of visual sensitivity should be conducted under conditions where oculomotor activity is constant and sufficient to preserve optimal visual sensitivity. If oculomotor activity is not constant under the different experimental conditions, and if the experiment is not concerned with elucidating the differences in visual sensitivity which accompany differences in oculomotor activity, then the experimenter (E) is left with the uncomfortable task of deciding whether the changes in visual sensitivity observed were caused directly by his manipulations or indirectly by saccadic suppression.

Fixation stability is also an implicit requirement when E wishes to specify the retinal locus of the critical visual stimulus. Usually, O is presented with a fixation marker at a known distance, and then on the assumption that the projection of the center of the fixation spot is on the center of the fovea or some other specified retinal point, a visual

stimulus is presented in some spatial relationship to the fixation marker. If O's eye moves, the projection loci on the retina of both the fixation marker and the visual stimulus will be incorrect relative to that specified by E, though the distance between the fixation marker and the stimulus remains constant.

As an illustration, suppose E analyses the conditions necessary to assure accuracy of the statement: "a 1° test flash was presented to the fovea." This example is not arbitrary; the experiment described in this report derived from consideration of this statement. In order to assure accuracy of retinal locus of stimulation, it is necessary to guarantee that O fixates foveally and without interruption a (e. g. 18' arc) target whose center is projected onto the center of the fovea. Under these conditions, a 1° test flash, presented so that its center is also projected on the center of the fovea, falls totally within the fovea. Figure 5 shows the fovea in some assumed position with a fixation spot and a representation of the test flash centered on it. In this position, O accurately fixates the fixation spot. Also shown is a new position for the fovea, following a 24' arc eye movement to the left. In this position, it is still true that the stimulus flash is totally on the fovea. Any more

Fig. 5. Fovea drawn to scale in an originally specified position and following a 24' arc eye movement to the left. Projected onto the center of the fovea in the original position is an 18' arc diameter fixation spot, a 48' arc diameter area specifying the limits of acceptable fixation, and a 1° arc diameter test flash. Following the 24' arc movement to the left, the 1° test flash is still totally within the fovea. Foveal diameter is assumed to be 2°.


1° FLASH
ACCEPTABLE
LIMIT OF FIXATION
ORIGINAL
POSITION OF
FOVEA
24'
9'
EYE TO LIMIT
OF FIXATION
24' movement
FIXATION
SPOT
POSITION
OF FOVEA AFTER
24' MOVEMENT TO LEFT

than 6' arc additional movement to the left would result in some portion of the stimulus flash being off the fovea. Thus presentation of a 1" test flash to the fovea is assured only when the retinal projection of the center of the fixation spot is within 30' arc of the center of the fovea. Compensation for errors in alignment is provided if this calculated radius is reduced by 20% to 24' arc.

Stabilized image technique is a first approximation toward solution of the problem of operationally assuring accuracy of retinal locus of stimulation. If the stimulus is attached to the contact lens, the retinal locus of stimulation remains constant in spite of eye movements ($\pm$ error due to slippage of the lens when the eye executes saccades greater than 5°). If the stabilization technique used involves a compensating optical system (Riggs, Ratliff, Cornsweet, and Cornsweet, 1953), it is theoretically possible to assure that the fixation target actually falls on (e. g.) the center of the fovea and that stimulation will be delivered to some precise retinal region.

Although assuring accuracy of retinal loci in spite of eye movements, stabilized image technique introduced at least two major problems into visual sensitivity and perceptual (e. g. reversible figure) experiments: (1) the rate of change of the position of the image on the retina is so low that the

image has a tendency to fade on prolonged (i. e. a few sec.) exposure, and (2) oculomotor activity is not restricted by stabilization. Failure of stabilization to restrict oculomotor activity assumes importance because the locus for saccadic suppression may be central (Volkmann et. al., 1968). If the locus for saccadic suppression is central, stabilization may, by its inability to restrict oculomotor activity, not only fail to eliminate the reduction of visual sensitivity associated with saccades, but also adds to this reduction a retinal contribution. Consequently, it is of some importance that a technique be developed which (1) assures that stimuli will be presented only when O has met E's fixation requirements both spatially and temporally and (2) restricts oculomotor activity to the range required to assure optimal visual sensitivity.

Initially, it was planned to restrict oculomotor activity during fixation and to observe the effect of such restriction on detection thresholds. A system was designed to monitor eye position and to trigger stimuli only when O had met E's fixation requirements both spatially and temporally. Preliminary studies revealed that although the system functioned, O was rarely able to maintain spatial accuracy and temporal continuity to a reasonable criterion. Quite by accident, it was noted that oscilloscopic display of the fixation transducer output - display

visible to O improved fixation performance. These observations suggested that the assumption of accurate fixation as a continuous event needed re-examination, and that the effect of feedback on fixation performance ought to be investigated. The study to be reported was designed (1) to examine the assumption that O keeps the projection of the center of the fixation spot on the center of some retinal point (+ allowable error) throughout a trial, (2) to determine the effect of feedback (visual and/or auditory) in improving O's fixation performance, and (3) to provide a technique to assure that visual stimuli are presented only when O has met some specified spatial and temporal fixation criterion.

METHOD AND APPARATUS

Experimental design

A repeated-measures design was used (1) to examine the assumption that accurate fixation is a continuous event and (2) to assess the effect of feedback and practice on fixation performance.

Fixation was observed in dim light (clearly photopic) under nine fixation conditions. Four of the conditions provided feedback (FB) regarding accuracy of fixation and four of the conditions provided no such feedback (NFB). The ninth condition provided feedback in two modalities.

The nine fixation conditions were derived by manipulating the illumination of the fixation target and the presence of an auditory signal. The fixation spot, a light emitting diode (LED) could be (a) continuously off, in which case it appeared black, (b) continuously on, in which case it appeared red, or (c) intermittently on, with illumination contingent upon O being on fixation. Sound, a 2600 Hz (nominal frequency) tone, could be (a) off throughout the trial, (b) on throughout the trial, or (c) intermittently on, with presence being contingent upon O being on fixation. Each condition of light was paired with each condition of sound. The nine fixation conditions are shown in Table 1.

Each O was run through the series of fixation conditions once on each of four consecutive days. The order of presentation

Table 1

The Fixation Conditions

Illumination of Fixation Target	Auditory Signal	Symbol
off	off	L-S-
off	on	L-S+
off	feedback (FB)	$L-S_{fb}$
on	off	L+S-
on	on	L+S+
on	feedback (FB)	$L+S_{fb}$
feedback (FB)	off	$L_{fb}S-$
feedback (FB)	on	$L_{fb}S+$
feedback (FB)	feedback	$L_{fb}S_{fb}$ (a)

[a] The double feedback condition was used for calibration. It was therefore eliminated from all analyses in which the effect of feedback was evaluated.

of conditions was randomized.

Subjects

Three graduate students at Queens College of the City University of New York served as volunteer observers. All Os had 20/20 Snellen scores, normal color vision, and no measurable astigmatism.

Procedure

A limbal reflection technique was used to detect whether O viewed continuously for 90 sec. and with the same part of his retina a spot subtending 18' arc presented 1.83 m. from his left eye in the frontoparallel plane. O's right eye was occluded and his head was stabilized on a bite board, chin rest, and head rest. The bite board assembly and the chin and head rest assembly were each adjustable along the X, Y, and Z axes. O was positioned and instructed and the system was calibrated. E then set the tone and light condition, called "ready", cleared the system, and began the trial. The interval between the end of calibration and start of trial was give sec.

Instructions to subjects. -- "You are to fixate the fixation spot with your left eye. Your right eye will be covered and you will be stabilized on a bite board, chin rest, and head rest. Your task is to fixate the spot as accurately as possible during the entire trial. The trial

will last 90 sec.

"Sometimes the fixation spot will be self-illuminated (red) throughout the trial. Sometimes the fixation spot will be unilluminated throughout the trial. If it is unilluminated, it will look like a black dot. Sometimes the spot will be both illuminated and unilluminated in the same trial. If this is the case, then illumination accurately reflects your fixation performance. In other words, the spot will be illuminated when you are on fixation, and it will be unilluminated when you are off fixation.

"There will also be three conditions of tone: never on, intermittently on, and always on. Again intermittency will accurately reflect your performance: the tone will be on when you are on fixation and the tone will be off when you are off fixation. Each tone condition will be paired with each illumination condition. You will be calibrated to 'on fixation' before each trial, and each trial will begin with a 'ready' call from the experimenter."

Apparatus

Optics. -- Light from a 12 volt direct currend (VDC) helical-filament bulb was focused on the left lateral limbal tangent of O's left eye. The incident angle of the light beam was such that when O was fixating the fixation spot, or any point with 15' arc from the spot's perimeter,

the reflected beam (from the eye) was focused on the active surface of a silicon avalanche photodetector[2]. The optical arrangement is shown in Figure 6.

The filament was placed at the focal plane of a 100 mm. focal length achromatic lens. The lens therefore, served to collimate the light. Collimation served two purposes: (1) it allowed introduction of a filter and iris such that these components would not alter the light path and (2) it prevented the loss of intensity (as would occur with a non-collimated beam where intensity falls off with the square of the distance). Another lens,of identical characteristics, was placed in the path of the collimated beam 100 mm. from the limbal surface. This lens served to form an image of the filament on the limbus. An iris with a 2 mm. opening was placed between the two lenses, as was a removable Kodak Wratten 88 A (infra-red) filter. The iris restricted the spot on the eye to the limbus, and the filter, which was inserted after O was aligned, made the light beam essentially invisible.

Light from the filament image on the limbus was collimated by a third 100 mm. focal length achromatic lens and another image was formed on the active surface of the

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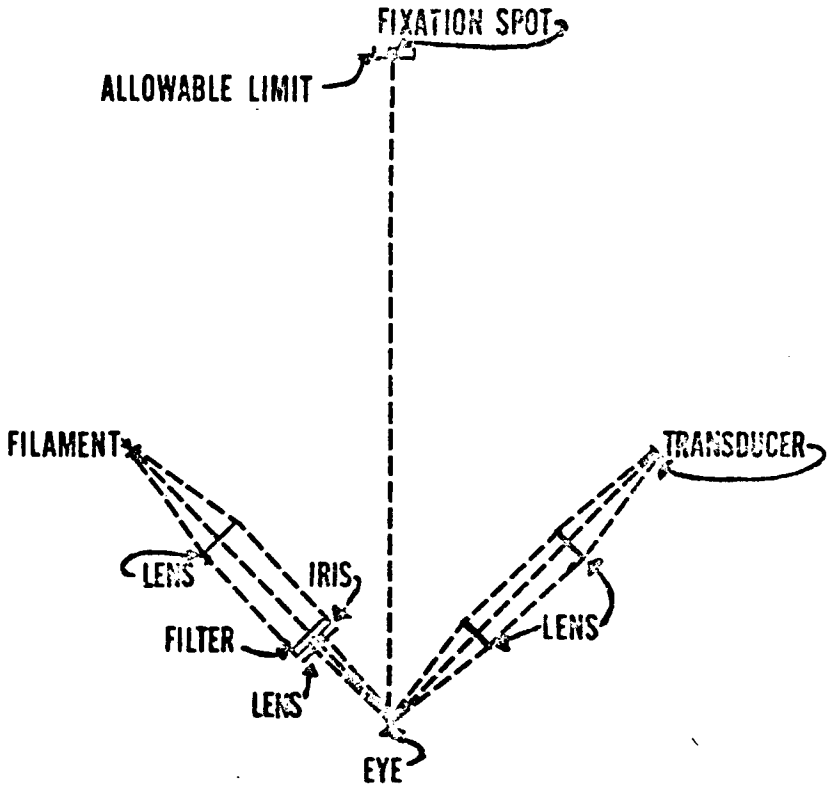
[2]The photodetector, loaned to the author by W. N. Shaunfield of Texas Instruments, was a prototype model.

Fig. 6. Schematic of optical system, not to scale, showing incident light beam, reflected light beam, fixation axis, and optical components.


FIXATION SPOT
ALLOWABLE LIMIT
FILAMENT
TRANSDUCER
LENS
IRIS
FILTER
LENS
LENS
EYE

silicon avalanche photodetector by a fourth 100 mm. focal length achromatic lens. The photodetector was positioned so that it was maximally illuminated when O viewed the center of the fixation spot. Intensity of illumination on the photodetector decreased in an analog fashion as O moved his gaze away from the center of the fixation spot.

Calibration. -- The phototransducer and its associated circuitry were adjusted to indicate on whenever O viewed any point within 24' arc from the center of the fixation spot, and off if O moved his gaze beyond these limits. Calibration was obtained by instructing O to visually track a pointer which was moved back and forth between two points, each one of which was located 24' arc from the center of the fixation spot. The transducer was positioned and its reference voltage adjusted such that when the pointer (and presumably O's gaze) passed the 24' arc limit of fixation (9' arc radius of spot + 15 arc annulus of limit) the transducer signal indicated O was off fixation. When the pointer and O's gaze were brought back within the limits of fixation, the transducer indicated on. The adjustment was repeated until the transducer signal consistently changed state at the indicated point. O received feedback in both modalities (light

and sound) during this procedure. Calibration was checked between each trial in the run.[3]

Electronics[4] The output of the photodetector was connected as one input to a voltage comparator (Figure 7). The other input to the comparator was an adjustable reference voltage. The reference voltage was set such that the detector voltage would exceed the reference voltage whenever O viewed the fixation spot or any point within 15' arc from the spot's perimeter.

When O was on fixation, the comparator output was high. This output remained high until O moved his gaze outside the allowable area at which time the comparator output went low.

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[3] O_1 was not calibrated to "on fixation" before each trial in runs one and two. She was calibrated to "on fixation" before each trial in runs three and four. Data from O_1 was included because there was no difference in her performance during those runs in which she was calibrated before each trial and those runs in which she was not calibrated before each trial.

[4] Electronic circuits, logic functions, apparatus checkpoints and components are shown in Appendix I.

Fig. 7. Voltage comparator circuit showing analog to digital conversion of signal indicating deviation from fixation. Transducer output (TI) is proportional to the intensity of light on the photodetector. Limits of fixation are defined electrically as: on = TI > reference voltage, off = TI < reference voltage. Comparator output amplified to + 12 VDC in on state and ground in off state.

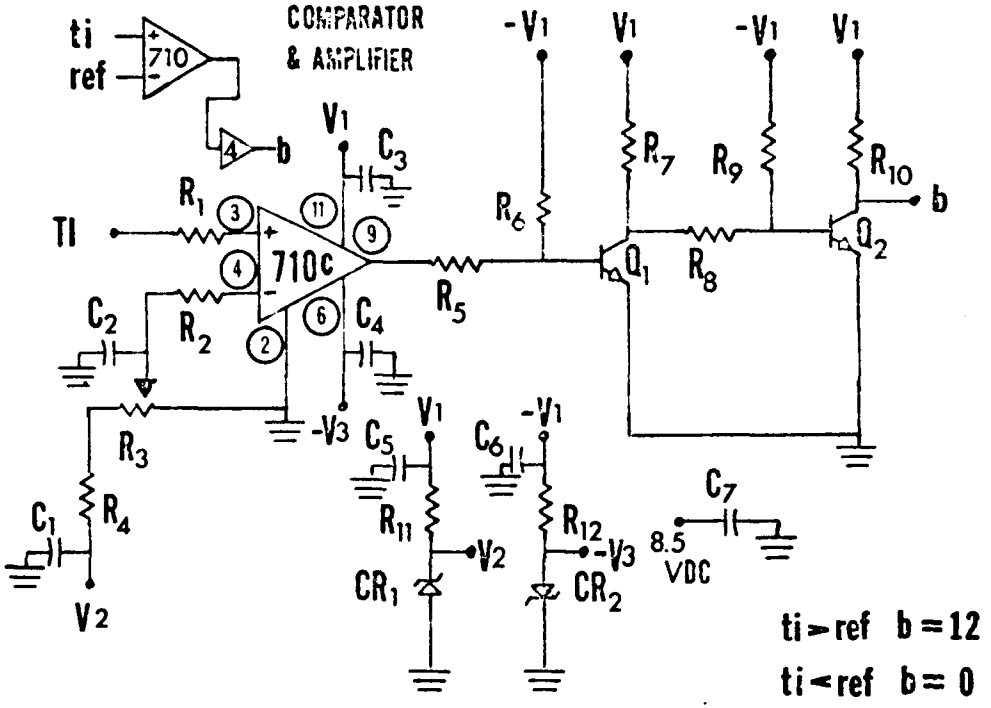
ti
ref
710
COMPARATOR
& AMPLIFIER
b
V1
C3
R1
TI
3
11
9
4
710c
6
2
C2
R2
C4
R3
-V3
R4
C1
V2
R6
-V1
V1
R7
R9
-V1
V1
R10
b
Q1
R8
Q2
R5
V1
C5
R11
V2
CR1
-V1
C6
R12
-V3
CR2
C7
8.5
VDC
ti>ref b=12
ti<ref b=0

Figure 8 shows a simple schematic of the system used to obtain the trial and fixation records and to control the illumination of the fixation spot and the presence of sound. In the feedback conditions, the auditory and visual signals were driven by the fixation transducer output, whereas in the no feedback conditions these signals were derived from external voltage sources. A complete description of the system is given in Appendix I.

The system as designed included a constrained fixation stimulus trigger sub-system. This sub-system, also described in detail in Appendix I, allowed for the presentation of stimuli if, and only if, O met E's fixation requirements both spatially and temporally. Excursions from fixation automatically reset the system to t=0.

Data collection. -- The trial records and fixation record were recorded on a Harvard Apparatus Recorder[5]. Chart speed was 41 mm/sec. A one sec. time marker was also displayed on the record. The fixation record was read to the nearest half mm. by the trial duration in mm. and multiplying by 90. The record was read continuously (i. e. not sampled).

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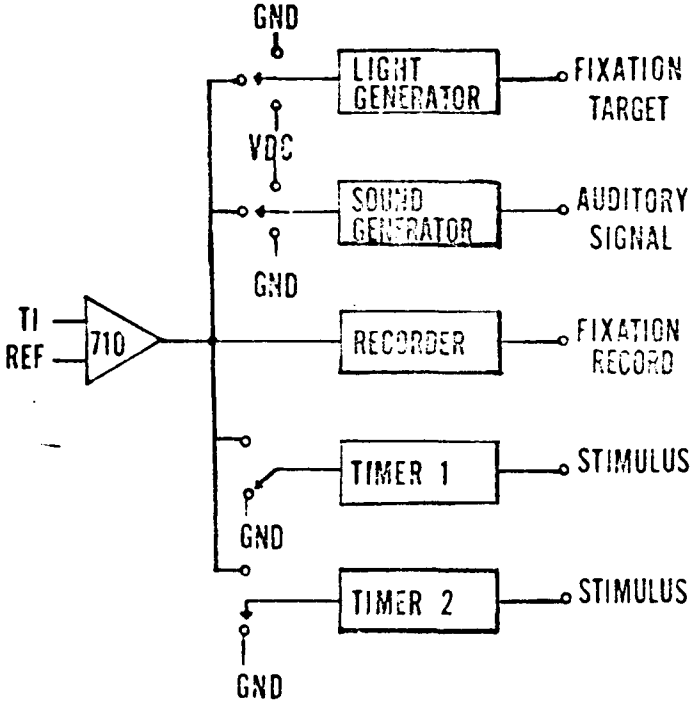
[5]Harvard Apparatus Corp. Model No. 450 and pen driver Model No. 350.

Fig. 8. A simple schematic of the system used to obtain trial and fixation records and to control the illumination of the fixation target and the presence of the auditory signal.


GND
LIGHT GENERATOR
FIXATION TARGET
VDC
SOUND GENERATOR
AUDITORY SIGNAL
GND
TI
REF
710
RECORDER
FIXATION RECORD
TIMER 1
STIMULUS
GND
TIMER 2
STIMULUS
GND

RESULTS

A summary of the data is shown in Figures 9-12. Figure 9 shows the mean cumulative fixation duration with and without feedback for each O for 1, 10, and 90 sec. fixation intervals. The fixation duration is shown both in sec. and in percent of the fixation interval. Figures 10-12 show the time course over which the cumulative fixation duration developed (cumulative time on target as a function of time in trial). The dashed line represents the predicted fixation function for continuous fixation. FB and NFB are the functions obtained with and without feedback (N=16 for each point). A more complete presentation of the data may be found in Appendix II. Each figure in the appendix shows time on target as a function of time in trial for each O in each of the four sessions (1, 2, 3, 4).

Figures 9-12 reveal discontinuity of fixation throughout the fixation trial under all conditions. In Figure 9, the mean cumulative fixation duration is never equal to the length of the fixation interval (the characteristic of continuity) even when the fixation interval is as short as one sec. In Figures 10=12, discontinuity is shown by the deviation of the obtained cumulative fixation during function from the predicted fixation function.

Fig. 9. Mean fixation duration (and 95% confidence intervals) with and without feedback.

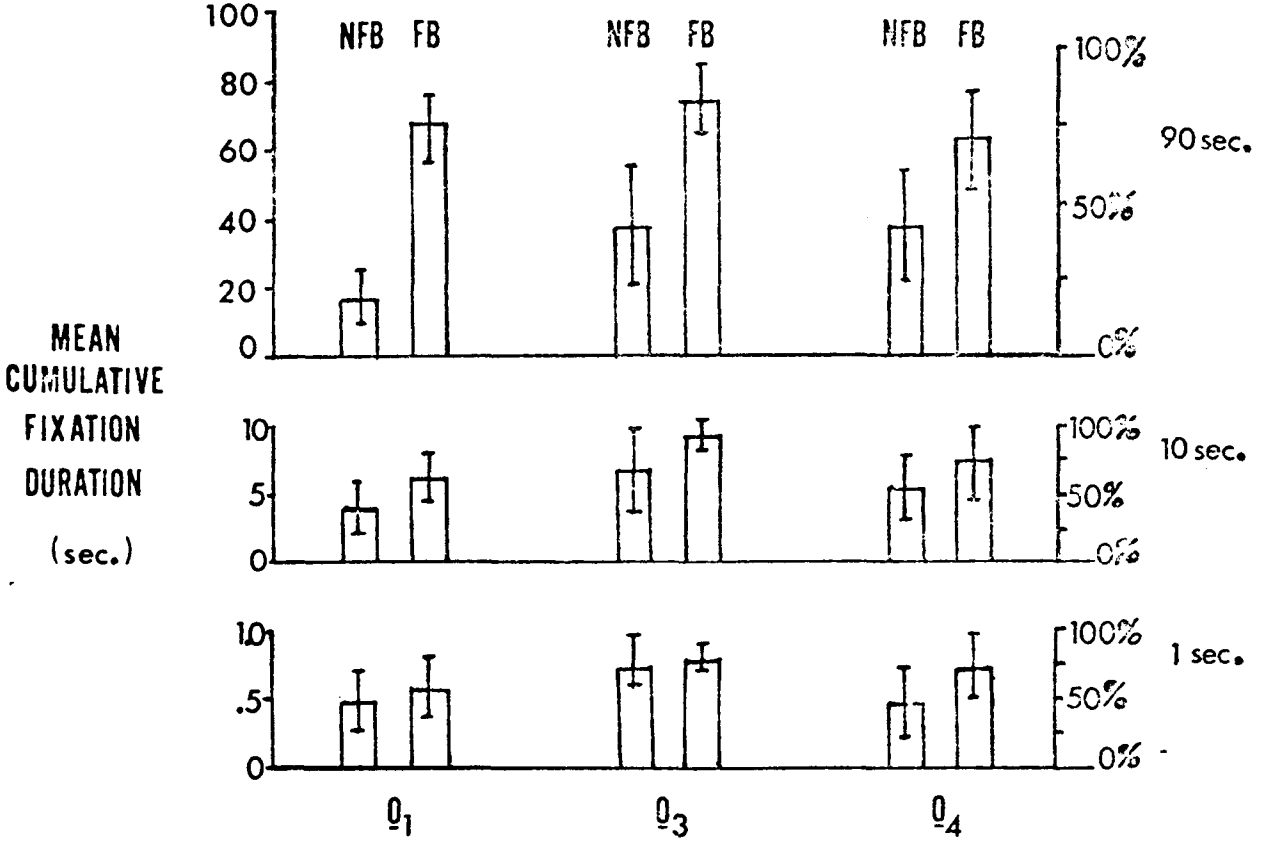

MEAN CUMULATIVE FIXATION DURATION (sec.)
100
80
60
40
20
0
NFB FB
NFB FB
NFB FB
100%
50%
0%
90 sec.
10
5
0
10 sec.
1.0
.5
0
1 sec.
O_1
O_3
O_4

Fig. 10. Time on target with and without feedback as a function of time in trial. $\underline{0}_1$.

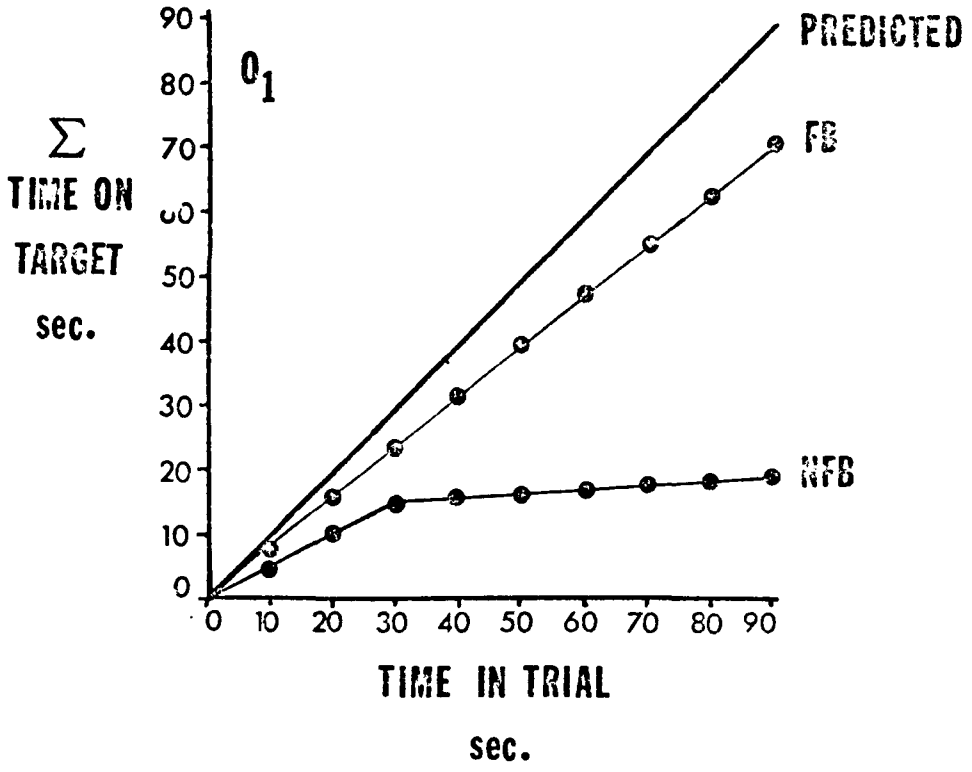

90
80
70
60
50
40
30
20
10
0
O_1
PREDICTED
FB
NFB
Σ
TIME ON
TARGET
sec.
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.

Fig. 11. Time on target with and without feedback as a function of time in trial. $\underline{O}_3$.

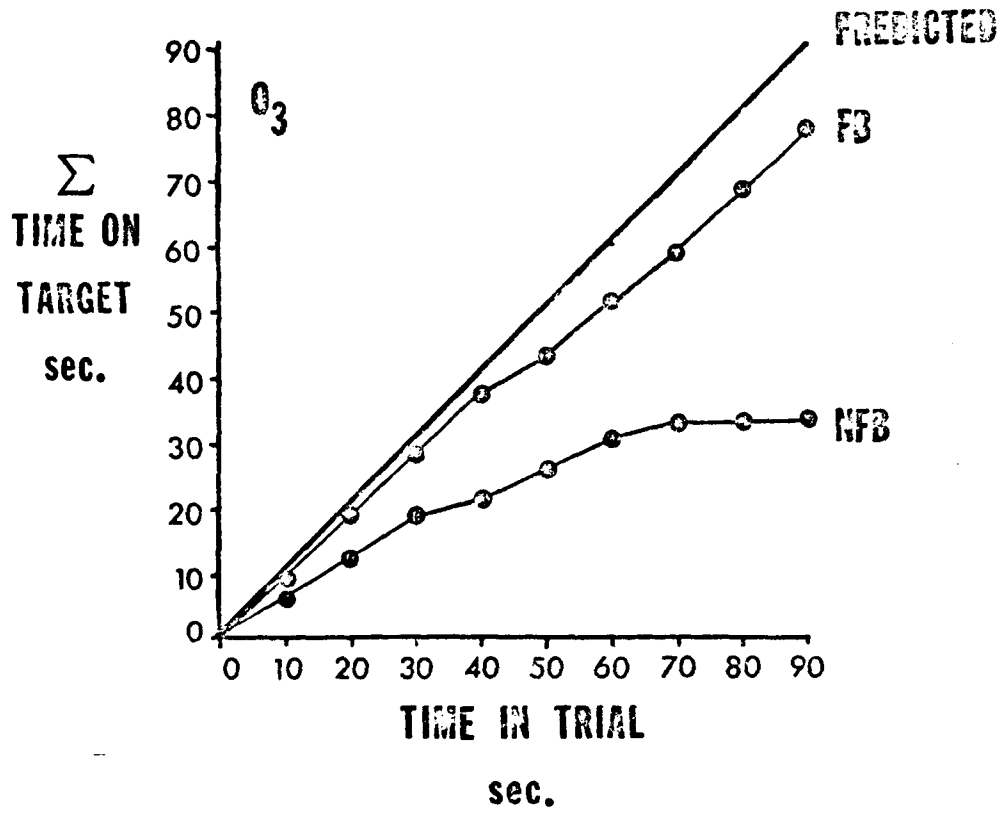
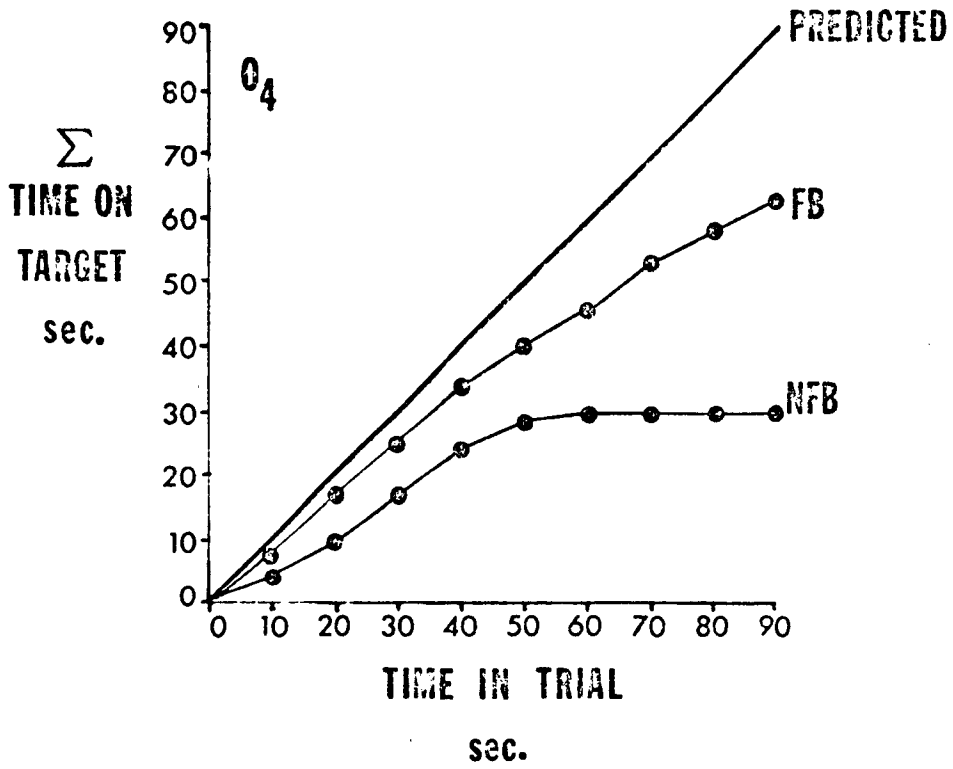

PREDICTED
FB
NFB
O_3
Σ TIME ON TARGET sec.
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL sec.

Fig. 12. Time on target, with and without feedback, as a function of time in trial. $\underline{O}_4$.


PREDICTED
FB
NFB
O_4
Σ TIME ON TARGET sec.
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL sec.

The figures also show that the effect of feedback was to increase the cumulative fixation duration. When O received no experimental feedback, the cumulative fixation function reached an asymptotic value at 30-60 sec. into the trial. When O obtained experimental feedback, the observed fixation function and the predicted fixation function were similar. However, there was a small but continuous departure from the predicted fixation function.

Continuity of fixation. -- Continuous fixation means that O kept the projection of the center of the fixation spot within 24' arc of the center of some operationally defined constant retinal area without interruption for the required period. Table 2 shows the frequency with which this criterion was met in each condition for 1, 10, and 90 sec. fixation intervals. Chi square analyses were used to test the hypothesis that there was no difference between the observed and predicted frequency with which Os met the criterion of uninterrupted (i. e. continuous) fixation. These analyses are shown in Table 3. For each fixation interval tested, the hypothesis was untenable ($X^2_{1\text{ sec.}}=28.42$, $X^2_{10\text{ sec.}}=67.33$, $X^2_{90\text{ sec.}}=106.08$; df = 8, $p < .001$). These results are also shown graphically in Figures 9-12. If O fixated continuously, the cumulative fixation functions would be coincident with the predicted fixation functions and the mean fixation duration

Table 2

Frequency of Trials During Which Os Maintained Uninterrupted Accurate Fixation

Fixation		Condition								
Interval	Light	Off	Off	Off	On	On	On	FB	FB	FB
	Sound	Off	On	FB	Off	On	FB	Off	On	FB
1 sec.		8	2	7	5	5	6	7	7	8
10 sec.		5	0	4	2	1	2	5	2	3
90 sec.		0	0	0	0	0	1	1	0	0

Note. -- Combined data from all three Os . The maximum possible frequency in each condition is 12.

Table 3

Summary of Chi Square Analyses: Differences Between the Observed and Predicted Frequencies With Which Os Maintained Uninterrupted Accurate Fixation

	Fixation Interval		
	1 sec.	10 sec.	90 sec.
X^2	28.42	67.33	106.08
df	8	8	8
p	$<.001$	$<.001$	$<.001$

Note. -- The literature implies that O is expected to maintain accurate fixation; thus the predicted frequency is equal to the number of trials presented. The observed frequency for each condition is shown in Table 2.

would be equal to the trial duration. Clearly, this was not so.

Chi square analyses were used to test the hypothesis, that the frequency of trials during which O fixated continuously was unrelated to the presence or absence of feedback. These analyses are shown in Table 4. In each case (1, 10, and 90 sec.) the hypothesis was tenable.

Effect of feedback and practice on total fixation duration.-- Table 5 shows the summary of the analyses of variance used to test the main effect of feedback and practice (runs on consecutive days) on total fixation duration (Kirk, 1968, p. 239). Feedback was significant in raising total fixation duration within each interval ($F_{1\ sec.}$ =16.05, $F_{10\ sec.}$ =12.61, $F_{90\ sec.}$ = 33.79; df = 1, 14, $p < .01$). The graphical presentation of these findings are again shown in Figures 10-12. Without feedback, O fixated intermittently for the first 40-60 sec. and then wandered off fixation and stayed off fixation. With feedback, O tended to maintain fixation throughout the trial. That fixation with feedback, though improved, is not continuous is again shown by the deviation of the fixation function with-feedback from the predicted fixation function.

The main effect of practice failed to reach significance ($F_{1\ sec.}$ = 0.64, $F_{10\ sec.}$= 1.17, $F_{90\ sec.}$ = 0.275; df = 3, 14, $p. > .05$). These results are presented graphically in Appendix II. Within each condition, there was no systematic improvement

Table 4

Summary of Chi Square Analyses:

Continuity of Fixation With and Without Feedback

Fixation Interval	Condition		Continuous Fixation		Interrupted Fixation
1 sec.	No FB	Obs. f	20.		28.
		Pred. f	23.5		24.5
	FB	Obs. f	27		21
		Pred. f	23.5		24.5
		X^2		2.04	
		df		1.	
		p		$>.05$	
10 sec.	No FB	Obs. f	8.		40.
		Pred. f	10.5		37.5
	FB	Obs. f	13.		35.
		Pred. f	10.5		37.5
		X^2		1.42	
		df		1.	
		p		$>.05$	

Table 4 -- Continued

Fixation Interval	Condition		Continuous Fixation	Interrupted Fixation
90 sec.	No FB	Obs. f	0.	48.
		Pred. f	1.	47.
	FB	Obs. f	2.	46.
		Pred. f	1.	47.
		X^2	2.04	
		df	1.	
		p	$>.05$	

Table 5

Summary of Analyses of Variance:

Effect of Feedback and Runs on Cumulative Fixation Duration

Fixation Interval	Source	df	MS	F	p
1 sec.	Blocks (Os)	2	3.1926	5.89	<.05
	Treaments	7	.4887		
	FB/NFB	1	8.6938	16.05	<.01
	Runs (R)	3	.3487	.64	
	FB x R	3	.4035	.74	
	Residual	14	.5416		
10 sec.	Blocks (Os)	2	233.8015	5.88	<.05
	Treatments	7	125.2381		
	FB/NFB	1	501.0914	12.60	<.01
	Runs (R)	3	46.5636	1.17	
	FB x R	3	78.6283	1.97	
	Residual	14	39.7487		
90 sec.	Blocks (Os)	2	5641.72	1.38	>.05
	Treatments	7	21039.46		
	FB/NFB	1	138298.91	33.79	<.01
	Runs (R)	3	1133.81		
	FB x R	3	1858.62		
	Residual	14	4092.34		

in fixation performance across days.

Effect of fatigue on fixation performance. -- The effect of fatigue on fixation performance was assessed via a Kendall coefficient of concordance. The analyses are summarized in Table 6. The cumulative fixation durations within a run were ranked, and that rank assigned to the position of the trial within the run, without regard for the type of trial presented in that position. The results were evaluated to determine whether there was any relationship between position with a run and the total fixation duration during that trial. The Kendall coefficients of concordance indicated that, for all fixation intervals examined (1, 10, and 90 sec.), there was no relationship between position within a run and cumulative fixation duration.

Table 6

Summary of Kendall Coefficients of Concordance: Effect of Position of Trial Within Run on Cumulative Fixation Duration

	Fixation Interval		
	1 sec.	10 sec.	90 sec.
w	.111	.088	.117
X^2	10.6	8.45	10.56
df	8	8	8
p	$>.10$	$>.30$	$>.10$

DISCUSSION

The results obtained in this study may be summarized as follows: Os instructed to fixate a marker did not maintain fixation within 24' arc of the initial fixation axis without interruption for the required duration, even when the required duration was as short as one sec. Feedback, either visual or auditory, produced a significant increase in the total time spent on fixation in any given trial. Within the limits of this experiment, fixation performance did not improve with practice across days, nor did it deteriorate with fatigue.

An unexpected finding in this study was the intra-trial deterioration of fixation. In the no-feedback conditions, fixation deteriorated such that at the end of 30-60 sec., O rarely fixated anywhere within 24' arc of the center of the fixation spot (Figures 10-12). That this finding was unrelated to fatigue was demonstrated in two ways: (1) external feedback, which does not influence fatigue, improved intra-trial performance, and (2) fixation performance without feedback was unrelated to position of a trial within a session.

Previous studies have shown that eye movements during monocular fixation may change substantially the position of the fixation axis (Barlow, 1952; Ratliff and Riggs, 1950, p. 695; Yarbus, 1967). Nachmias (1959) disagreed with these

conclusions, suggesting instead that the fixation axis remains within 5' arc of its original position 68% of the time in 30 sec. trials. It appears that the differences between Nachmias' observations and the observations both in this study and in the cited literature derived from Nachmias' sampling technique. "Only those 30 sec. runs were selected for measurement which produced sharp photographic traces free of progressive, uncompensated drifts; an entire run was rejected if any part of it appeared unsatisfactory. This was done to eliminate runs during which either poor fixation or appreciable contact lens slippage had taken place" (Nachmias, 1959, p. 902; italics mine). This technique eliminates from the estimate of fixation instability those trials during which O showed appreciable fixation instability; the logic of such sampling can be questioned. When fixation records are analyzed continuously (as in Figures 10-12), rather than sampled, and when all fixation trials are included in the analysis, a more representative measure of fixation stability is obtained.

The number of trials during which O fixated without interruption within 24' arc of the center of the fixation spot decreased as duration of the fixation interval increased. There were 55 trials (of 108) during which O maintained accurate fixation for the first sec. of fixation. This number decreased to 24 when the required interval of fixation was increased to 10 sec. When the

required interval of fixation was 90 sec., accurate fixation was observed to be continuous in only two trials. Out of 48 no-feedback trials (the usual fixation condition specified in the literature), uninterrupted fixation was observed during 20 trials when the required fixation interval was one sec., during 8 trials when the required fixation interval was 10 sec, and in no trials when the required interval was 90 sec.

Figures 10-12 show (1) that fixation was unstable throughout the fixation interval and (2) that, as the duration of the fixation interval increased, the axis of fixation was in error a greater proportion of the time. Thus it must be concluded that the actual projection loci on the retina of stimuli in phychophysical experiments frequently deviate by more than 24' arc from that specified by E and also that the probability of such an error increases as the session progresses, particularly in those studies where fixation is presumed to be uninterrupted (infra: plotting of visual fields).

The finding of deteriorating fixation performance without feedback and improved fixation with feedback raises two issues: (1) why does the axis of fixation change as much as it was observed to change, and (2) how does feedback improve fixation stability.

In order to answer these questions, it might be helpful to consider the types of stimuli that affect the nervous system.

Among other things, the nervous system responds to magnitude and rate of change. Magnitude, for example, determines many absolute thresholds. Cooper, Daniel, and Whitteridge (1951) have shown that movement across the visual system must exceed a particular rate in order for O's nervous system to detect motion. In the visual system, a clear example of rate of change is flicker; in flicker, the rate is bounded on both extremes. If a light is modulated very slowly, flicker is not perceived (individual flashes are) and if a light is modulated very rapidly, the percept of flicker is replaced by the percept of a continuous light. The concept of rate of change implies that the nervous system can only integrate over a finite temporal interval; this point of view receives support from those studies which have demonstrated the reciprocity of intensity and duration in the visual system (e. g. Graham and Margaria, 1935). The reciprocity is limited to intervals of less than 100 msec. Beyond that exposure duration, intensity alone determines the nervous system response. Another example of rate of change as a determinant of perception is the phenomenon of Mach bands.

There are two possible sources of information regarding change in eye position. One source is visual and the other source is neural, presumably through the extra-ocular muscle spindle afferents. It is proposed that, during attempted fixation, the rate of change in eye position is sufficiently low

as to prevent either of these sources from providing accurate eye position information to the nervous system. This unavailability of eye position information results in fixation error.

The function of fixation is to hold an image on the retina in a position which maximizes the probability that the image will remain visible. This implies that the image should be projected foveally; it does not suggest that there is any survival value in holding the image on one part of the fovea as opposed to another part of the fovea. Evidence derived from stabilization literature suggests that maintaining the image without motion on one part of the fovea decreases the probability that a stimulus will remain visible, and evidence from saccadic suppression literature suggests that moving the image too rapidly also decreases the probability that a stimulus will remain visible. That suppression of visual sensitivity accompanies rapid changes in eye position has been shown both for micro-saccades which accompany normal fixation and for voluntary saccades (Beeler, 1967; Volkmann, Schick, and Riggs, 1968). Thus it seems likely that visually provided information as to change in eye position will be obtained only if that change in position occurs more rapidly than the changes necessary to maintain clear vision, and less rapidly than the changes which suppress vision (see Figure 3).

The other input which could provide signals to the nervous system that the eye has changed position derives from the muscle

(spindle) afferents. The literature is unclear as to whether the central nervous system receives neural "feedback" of eye position (Fuchs and Kornhuber, 1969; Collins, 1971; Granit, 1971; Merton, 1964). Even if it is shown that the muscle afferents do provide neural feedback of change in eye position, the essential question will remain - what is the necessary and sufficient stimulus which signals a change in eye position? The afferents from muscle spindles fire in response to a maintained load as well as in response to a sudden application of a load. All oculo-rotary muscles have a maintained load during fixation; in order to signal a change in eye position through the spindle system, it would be necessary to increase or decrease the rate of firing of the afferent. At what rate does eye position have to change to increase or decrease the rate of firing of the afferent and how much does the rate of firing of the afferent have to change before the central nervous system responds to the change? At the present time, the rate of change of eye position necessary and sufficient to signal the central nervous system is unknown. It may be possible to determine this rate of change if muscle spindle afferent output is recorded while the eye is rotated at different velocities. The determination of threshold acceleration for central nervous system feedback is important because it has been shown that most eye position

changes during fixation are caused by drift; drift typically has a velocity of 6' arc per sec. (Yarbus, 1967). If this rate of change is sub-threshold, then O would have no information that he has exceeded the limits of fixation.

External feedback (e. g. light or sound as in this study) can provide the error signal which is not normally derived from fixation instability. External feedback would thus serve to initiate voluntary search behavior and would affect only the voluntary eye movement system. That this explanation is compatible with the results obtained in this study is suggested by the fact that the effect of feedback was to increase the total amount of time within a trial that O spent on fixation, but not to effect the continuity of fixation. That feedback did not assure continuity of fixation was not surprising; with or without feedback, O attempted to maintain accurate,continuous fixation. Typically, when O drifts off xiation, he is unaware that he has done so. The feedback provided in this experiment alerted O that he was off fixation (in error) so that he could make a voluntary searching and possible corrective eye movement back to fixation. Feedback does not prevent the involuntary eye movement system from again moving the eye into a n error setting. Since yes/no feedback does not provide a warning of impending departure from fixation, it cannot assure continuity of fixation. Similarly. yes/no feedback does not provide O with information regarding the

degree and direction of his departure from fixation; therefore it cannot assure return to accurate fixation. It can, however, provide a signal that O is in error, thus initiating search, and it can provide a signal that O is no longer in error, providing an end-point for voluntary searching eye movement.

In many studies where locus of stimulation is specified it is necessary for O to maintain accurate fixation on command. In such studies, feedback would be an effective method for assisting O in performance of the fixation task. However, feedback by itself, provides no guarantee that O will be on fixation when stimuli are presented. One possible solution to the problem of guaranteeing accurate fixation and consequently guaranteeing stimulus presentation to the specified retinal locus, is to have a signal which indicates that O is on fixation trigger the critical visual stimulus. Such a signal was generated in the apparatus system described. As used in this experiment, the signal provided feedback to O. However, the apparatus was designed to provide the same signal to a stimulus trigger sybsystem. Such a system allows E to specify the spatial limits of accurate fixation and the temporal requirements of continuity. If O moves his gaze from the spatial loci specified by E before the temporally defined fixation criterion is met, the system resets itself; thus it assures that stimuli will

be presented to constant retinal loci (see Appendix I for details of the apparatus).

The remainder of this discussion will be directed to a consideration of the effect of fixation instability on the plotting of visual fields and the measurement of dark adaptation thresholds. These two areas have been chosen for discussion because they both require long duration fixation.

Influence of instability of monocular fixation on the plotting of visual fields.-- "Perimetry...is concerned with the field of the stationary eye..." (Scott, 1967, p. 1). Current perimetric techniques fail to assure that the eye, whose field is being plotted, is in fact stationary. This discussion is concerned with the consequences of this failure to assure fixation.

Perimetrists ordinarily depend upon direct observation of the eye as an index of visual fixation. If the perimetrist notes deviation from fixation, he repeats his measurement, after first reinstructing O to fixate. Ludvigh (1949) questioned how far gaze had to be shifted from fixation before an observer, whose only task was to monitor eye movement, detected the excursion. Ludvigh selected a card which instructed him to execute an eye movement of X° in Y direction. O signalled Ludvigh to move his eye, and then reported the direction of the observed movement. The results of this study indicated

that departures from fixation which were smaller than 1° could not be detected with the unaided eye. It is unlikely that the perimetrist, who must simultaneously monitor fixation and present targets, detects eye movements as small as 1°. This apparent failure to detect small deviations from fixation is important because fixation instability may explain various perimetric phenomena.

Hughes (1954) demonstrated that the finding of macular sparing is sometimes the consequence of fixation instability (pseudo-macular sparing). The error lies partly with the patient, who tends to swing his eye toward the blind field and adopt a new fixation point, and it lies partly with the observer, who may fail to detect fixation changes. Hughes advanced several large test objects (arranged in a vertical line) from the blind to the seeing field. When sparing was real, the central test object came into view first, and those at the periphery later. When sparing was apparent, and due to shift of fixation, all three objects appeared simultaneously.

Fixation instability may account not only for pseudo-macular sparing, but also for the failure to find sparing in patients with small lesions at the occipital pole. Patients with beginning involvement of the central field of vision usually complained of "blurred" vision or decreases acuity. It is probable that these patients show more fixation instability than

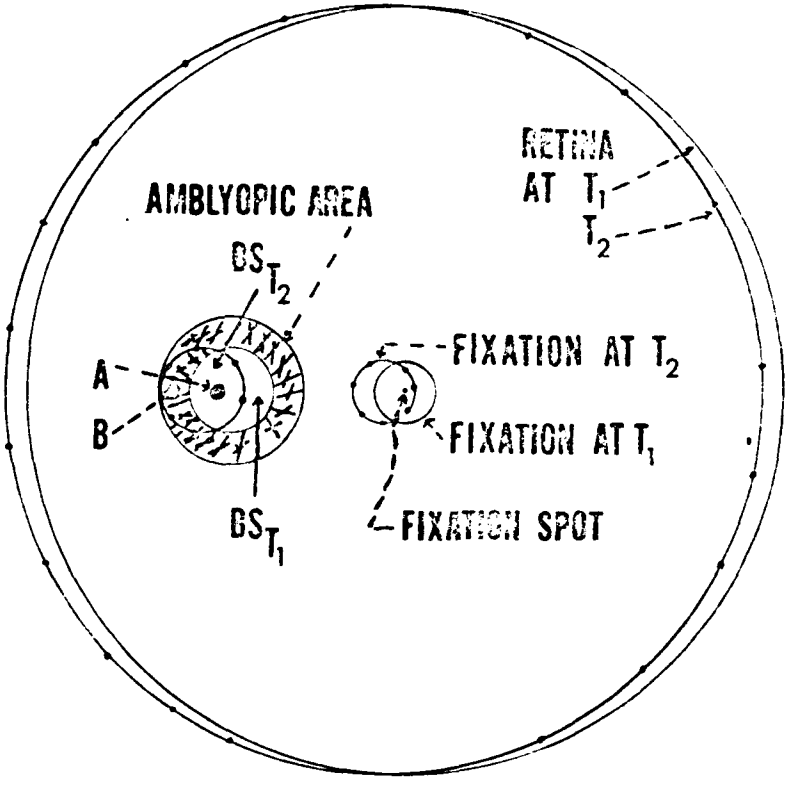
that observed in normals and not as much as that observed in hemianopics. This intermediate level of fixation instability would, at first, be effective in bringing the visual image onto intact portions of the macula. As the scotoma enlarged, however, fixation instability would be insufficient to hide the scotoma. Finally, as the scotoma enlarged to encompass the entire macula (or a large portion of it) O would unknowingly shift his fixation to a parafoveal locus, resulting in the false impression of macular sparing.

The other perimetric finding which may be associated with fixation instability is the presence of a 1° annular amblyopic zone surrounding the normal Blind Spot of Mariotte (as reported in Scott, 1957). The amblyopic zone is plotted by first outlining the blind spot with 5 mm. targets on a 1 or 2 m. tangent screen, and then examining the boundary of this blind spot with 1 mm. targets. When this is done, it is noted that there is a 1° annulus surrounding the blind spot within which O reports that the target is sometimes visible and sometimes not visible. Target detection improves as the target is moved closer and closer to the "intact" field. Data from the present study and from Boyce (1967), Ditchburn and Ginsborg (1953), Ludvigh (1949) and Yarbus (1967) support the argument that this zone is a statistical manifestation of fixation instability.

Normal eye movements during fixation (Boyce,1967; Ditchburn and Foley-Fisher, 1967; Ditchburn and Ginsborg, 1953; Yarbus, 1967) are such that at any instant, the position of the fovea may be up to 50' arc from the presumed position of the fovea; thus, normally, both the fovea and the optic disc are moved to continually changing positions. The consequences of this undetected fixation instability are shown in Figure 13. Any time the retina is at the position indicated at T_1, O is accurately fixating the fixation spot, and stimulus B will be projected onto a non-blind area of the retina. Whenever the retina is at the position indicated as T_2, the projection of the fixation spot is not at the center of the fovea, and stimulus B will be projected onto the blind spot. Since detection of stimulus B occurs part of the time, it will appear as if there is an amblyopic zone surrounding the blind spot and that this zone becomes more normal as it is plotted from the edge of the blind spot to the limits of the zone (i. e. there will be an amblyopic gradient). If the sizes of micro-saccades observed to occur during fixation are distributed normally, the amblyopic zone will appear to be more dense immediately adjacent to the blind spot than immediately adjacent to the "intact" surround.

It is possible that the amblyopic zone surrounding the blind spot, elicited only with 1 or 2 mm targets, can be accounted for wholly on the basis of poor acuity, but this seems

Fig. 13. The normal 1° annular amblyopic zone surrounding the Blind Spot of Mariotte viewed as a statistical phenomenon. Stimulus A will always be projected onto the blind spot. Stimulus B will sometimes be projected onto the blind spot and will sometimes be projected onto non-blind retinal areas. O reports the presence of B when the blind spot is in the position marked BS_{T1} and the non-presence of B when the blind spot is in the position marked BS_{T2}.


RETINA
AT T_1
T_2
AMBLYOPIC AREA
BS_{T_2}
A
B
FIXATION AT T_2
FIXATION AT T_1
FIXATION SPOT
BS_{T_1}

unlikely. The normal blind spot is centered approximately 16° temporal to fixation; it extends from 13° to 19° (Harrington, 1971, p. 102). If the annular amblyopic zone surrounding the blind spot resulted from poor acuity, it would be expected that there would be a measureable difference in the zone on the nasal and foveal sides of the blind spot, with target detection better on the foveal side of the amblyopic zone. This difference has not been reported, and in its absence, it is concluded that the amblyopic zone is statistical and not retinal in origin.

One solution to identifying the basis of the amblyopic zone might be to plot it with a stabilized image technique. If the finding of amblyopia persists even with stabilization, then the zone is not a statistical manifestation of fixation instability. If the finding of an amblyopic zone disappears with stabilization, then strong evidence to support the fixation instability hypothesis will have been obtained.

The finding of the present study that fixation instability persists even with feedback, requires that the techniques used to plot visual fields be re-examined. A possible solution to the problem of fixation instability is to make target presentation contingent upon fixation. The automatic system described in Appendix I can be adapted for clinical use, permitting both static and dynamic perimetry, contingent upon maintained fixation. The system would permit the plotting of visual fields even in

patients who hold fixation poorly, and would assure comparability of fields plotted at different times in the course of the disease.

Fixation instability and dark adaptation. -- The general variables influencing dark adaptation (increasing visual sensitivity with increasing time in the dark) are well known (Bartlett in C. Graham, 1966). The argument advanced in this discussion is (1) that fixation instability increases when the eye is placed in the dark, (2) that this fixation instability results in stimuli being presented to non-constant retinal loci, and (3) that the distribution of eye positions in the dark is not random but is related to the changing sensitivity of the eye. It is proposed that changes in eye position during the initial stages of dark adaptation, may systematically influence the shape of the early portion of the dark adaptation function.

Fixation instability appears to be maximized by the sudden transitions in illumination which occur at the beginning of dark adaptation. Steinman (1965) studied the effect of target sizes on fixation. In order for him to change the size of targets, it was necessary to close a shutter, obscuring not only the fixation target, but interrupting a steady state illumination of the eye. In discussing the eye movement records sampled, Steinman noted "Only the final 20 sec. of each 30 sec. trial were examined, in order to reduce variability arising from changes in adaptation that accompany changes in fixation targets" (p. 1159). Simon

(1904) used after-image mapping and blind spot mapping to determine fixation changes during an hour of dark adaptation. He noted an immediate 2° fixation shift associated with extinction of the adapting light, followed by a systematic shift of the fixation axis back towards the fovea during the course of dark adaptation. Further evidence of increased fixation instability associated with sudden changes in illumination comes from Matin, Matin, and Pearce (1970; see also Figure 14). Matin et. al. instructed their Os to maintain fixation and then extinguished all the lights (including the fixation target). In the three sec. interval immediately following the sudden change in illumination there were a large number of eye movements (mostly to the left) and the area over which the eye moved was considerable.

Eye movements associated with sudden changes in illumination result in stimuli being presented to varying retinal loci. The distribution of eye positions and consequently of stimulus loci may be related to the changing sensitivity of the eye, with the direction of gaze shift such that the fixation target is brought onto less sensitive retinal regions. That this interpretation is correct is suggested by the findings of Simon (1904) and Steinman and Cunitz (1968). In Simon's study, O redefined the retinal locus with which he viewed the fixation spot to be somethint other than that specified by E and over the course of an hour, O's fixation moved further and further away from that newly defined locus. The direction of gaze

Fig. 14. Frequency distributions of change in eye position during three sec. dark interval following extinction of fixation target in the dark. Reprinted from Matin, Matin, and Pearce, Vision Research, 1970, 10, 837-857.

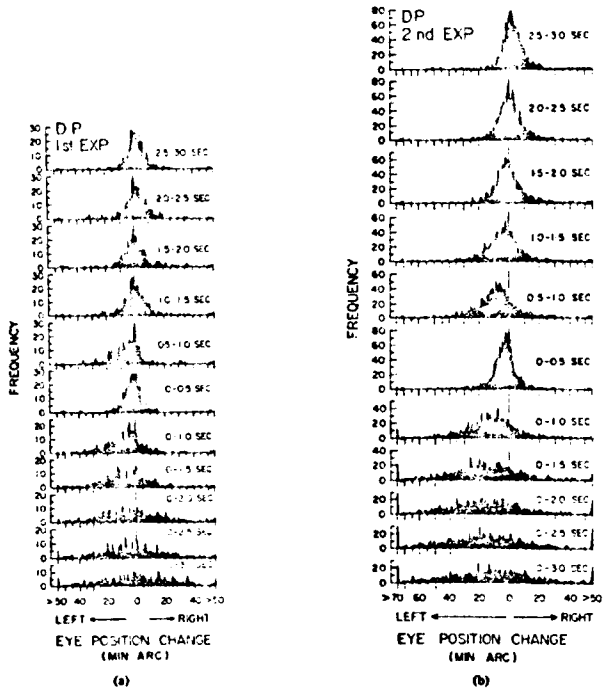


FIG. 1 (a) (b). Frequency distributions of change in eye position during the 3 sec dark interval. Each of the upper six graphs in each set is a distribution (over trials) of ocular displacements during the 0.5 sec indicated at the upper right of the distribution. Each of the lower six graphs in each set is a distribution of ocular displacements at a given moment in the dark interval as a deviation from the position of fixation at the beginning of the dark interval. The central graph in each set is common to both parts of the set. Data in each distribution are grouped at 1-min intervals along the abscissa. (a) Data for subject DP in Expt. 1. For each distribution $n = 360$. (b) Data for subject DP in Expt. 2. For each distribution $n = 1080$.

shift was such as to bring the fixation target onto a less sensitive retinal region (the parafovea is less sensitive than the fovea during early deark adaptation and the fovea is less sensitive than the parafovea during the later stages of dark adaptation). This incidentally, is precisely what Os in both this study and Yarbus' study did: in non-dark adapted eyes, the fovea is more sensitive than the non-foveal retinal regions and fixation shifts observed in the non-dark adapted eyes were away from the fovea. Os in Steinman and Cunitz's (1968) study were instructed to fixate small "white" light targets, the liminances of which were just above and just below foveal threshold. Os reported that the "subthreshold" targets disappeared periodically. Post session analysis of film records showed that Os began low luminance trials by rotating their eyes to fixate parafoveally; thus the low luminance targets were initially visible. Drift eye movements repeatedly moved the projection of the subthreshold targetrs closer to the insensitive foveal region. When the projection of the low luminance targets was foveal, the targets were no longer visible. "Target disappearances were followed by target-finding saccades that placed the target in a more sensitive retinal region... These experiments imply a reflexive guidance system that comes into play when the fixation spot is feeble. The system is maladjustive; it guides faint targets to a retinal

region where they cannot be seen" (p. 285). This finding lends support to the mechanism proposed to account for fixation instability and the effect of external feedback on fixation stability. In the dark-adapting eye, the disappearance of the fixation target provides an error signal which initiates voluntary searching eye movements and the reappearance of the fixation target provides an end-point for this search. Thus disappearance/reappearance and external feedback provide O with identical information. In neither the present study nor the dark adaptation studies is rate of change of eye position presumed to be sufficiently great as to provide a warning of impending departure from fixation, and in neither case does the feedback that fixation is no longer in error prevent error from reaccumulating and again moving the eye off fixation.

If eye position does change systematically during the early phases of dark adaptation, then these changes may directly influence the shape of the dark adaptation function. Two examples are derived from Hecht, Haig, and Walk (1935) and Crawford (1947).

Hecht, Haig and Wald (1935) reported the results of one dark adaptation determination in which a 2° test flash was presented to different retinal loci (0°, 2-1/2°, 5°, and 10°). The findings for 0° are presented in Table 7. Of particular interest is the observation that the "foveal" thresholds at 38.90

Table 7

Data from Hecht, Haig, and Wald (1935):

Results of One Dark Adaptation Determination at Zero Degrees

Time in Dark (min.)	Log I of F_t at Threshold
0.22	4.40
0.78	3.67
1.70	3.66
30.90	3.67
38.90	4.55
52.50	4.56

and 52.50 min. were higher than the original "foveal" threshold measured at 0.22 min. These findings cannot be explained photochemically; they may possibly be explained by fixation shifts. If Simon's measurements were accurate, then the first threshold determination was actually taken at 2° and not on the fovea. Consequently, no part of the test flash fell on the fovea. As dark adaptation continued, however, the fixation locus shifted toward the fovea. This could account for the rise in threshold seen in the latter part of the Hecht et. al. determination.

The other dark adaptation finding likekly to be associated with fixation instability is the observation by Crawford (1947) that threshold increases just before and just after the adapting light is extinguished. This cannot be explained photochemically. Extinction of the adapting light apparently results in saccadic eye movements; such eye movements, independent of when they occur, result in suppression of visual sensitivity (Beeler, 1967; Volkmann, 1962; Volkmann, Schick, and Riggs, 1968). Suppression appears to begin before the eye movement, but this may reflect a masking phenomenon. In any case, suppression raises thresholds by 1/2 log unit, and this is precisely the magnitude of the increment noted by Crawford in the dark adaptation curve. The similarity in magnitude and time course of Crawford's phenomenon and saccadic suppression suggest that the rise in the dark

adaptation function may be related to fixation instability, i. e. that the rise may be a saccadic suppression function superimposed on a dark adaptation function.

If saccadic suppression is a retinal phenomenon (Richards, 1968), then the rise in the Crawford dark adaptation curve will disappear under conditions of image stabilization. If, however, saccadic suppression is a central phenomenon (Volkmann, 1962; Volkmann, Schick and Riggs, 1968), stabilization will not provide an adequate test of the saccadic suppression hypothesis. The inadequacy of the method is, as previous suggested, related to failure to restrict oculomotor activity. The constrained fixation stimulus trigger system described in Appendix I may provide a technique for examining the hypothesis that saccadic suppression is responsible for the rise in threshold noted by Crawford. Prior to undertaking such a study, however, one would have to demonstrate that a saccade equal in magnitude to the diameter of the limits of fixation (specified by E) does not result in saccadic suppression. If such is found to be the case, and if the increment in Crawford's function derives from saccadic suppression, then the increment ought to "disappear" under conditions of oculomotor restriction.

This discussion is not meant to imply that all shift in dark adaptation thresholds over time should be attributed to fixation

instability. However, some of the demonstrated shifts in dark adaptation thresholds follow with revealing coincidence the demonstrated course of fixation changes during dark adaptation. It seems worthwhile to consider this variable in further detailed investigations.

SUMMARY

A repeated-measures design was used to examine the assumption that accurate fixation is a continuous event, and to evaluate the effect of feedback and practice on fixation performance.

O was considered to be fixating accurately if he kept his fixation axis within 24' arc of the center of its originally specified position.

Manipulation of illumination of the fixation target and the presence of an auditory signal generated nine fixation conditions, four of which provided no feedback regarding fixation accuracy, four of which provided feedback in one modality, and one of which provided feedback in two modalities.

With or without feedback, accurate fixation was discontinuous. Without feedback, fixation deteriorated such that at the end of 30-60 sec., O was no longer fixating the initial fixation spot or any point with 24' arc of its center. With feedback, O fixated, albeit discontinuously, throughout the trial. Feedback significantly raised total fixation duration within a trial. Practice did not improve fixation performance, and fatigue caused no deterioration in fixation performance.

It was proposed that the rate of change of eye position during attempted fixation was so low that neither the visual system nor the muscle spindle afferents signalled eye movement.

It was suggested that feedback improved fixation by providing O with an error signal, indicating that he was off fixation and initiating voluntary searching eye movements. The change in feedback signal when O again fixated provided an end-point for the search.

The consequences of fixation instability were discussed and a technique was described to make stimulus presentation contingent upon maintained fixation.

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APPENDIX I

Figure 15 shows a logical schematic of the circuits used to obtain the trial and fixation records and to control the illumination of the fixation spot and the presence of sound. The circuit checkpoint levels after clearing the system and before starting the trial are shown in Table 8 .

Start of trial (S-2) and end of trial (E) pulses were derived from a Hunter timer (Model No. 111 C). When a trial began, cutput D of flip-flops (FF) 1, 2, 5, and 7 went high. Consequently, point F was at 4.7 VDC and start of trial was indicated on the trial record.

If the fixation spot was not illuminated during the trial, switch 3 was at ground and switch 4 was at ground. If the fixation spot was continuously illuminated during the trial, switch 3 was at ground, switch 4 was at H, and the D cutput of FF_6 was high. If the illumination of the fixation spot was contingent upon fixation (i.e. if the trial was a light feedback trial), switch 3 was at TIBA, switch 4 was at ground, and the D output of FF_6 was low. If there was to be no auditory signal during the trial, switch 5 was at ground. If the auditory signal was continuously present during the trial, switch 5 was at 4.7 VDC. If the presence of sound was contingent upon fixation, switch 5 was at TIBA. If both the presence of sound and the illumination of the fixation spot were contingent

Fig. 15. Logical schematic of electronic circuits showing input (TI) and outputs [trial record, fixation record, sonalert, light-emitting diode (LED), and strobo-slave].

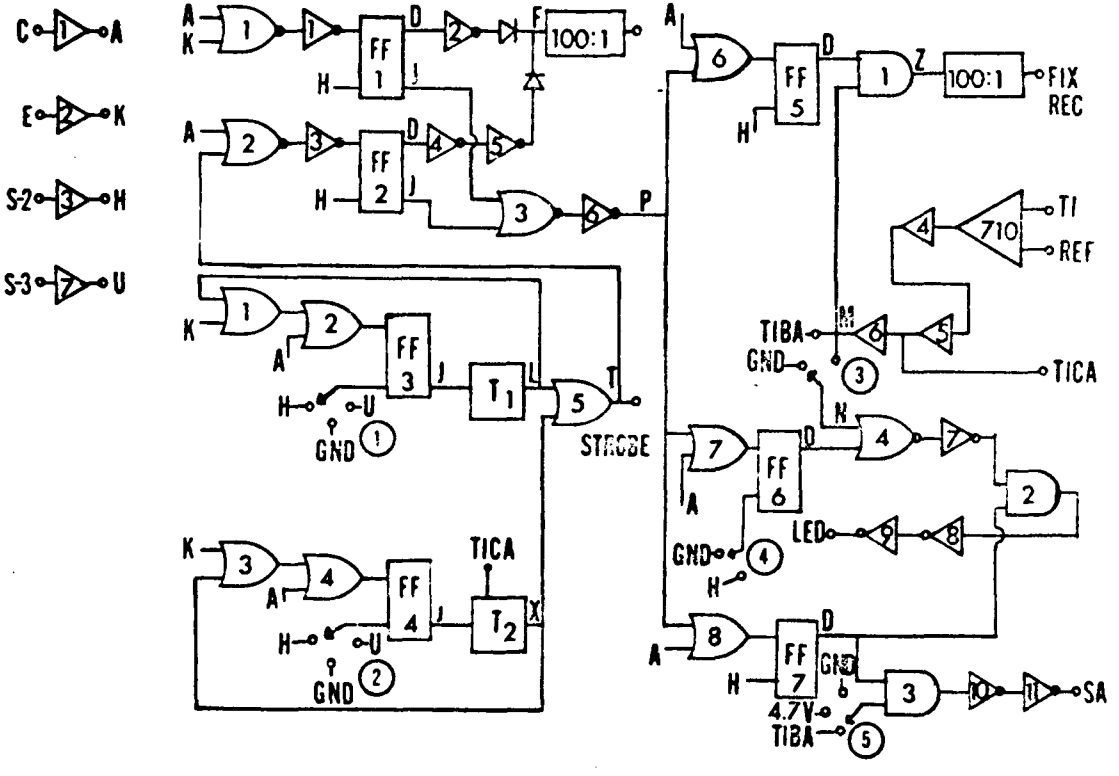

C
A
E
K
S-2
H
S-3
U
A
K
H
FF 1
D
F
100:1
A
H
FF 2
D
P
K
A
H
U
GND
FF 3
T1
STROBE
K
A
H
U
GND
FF 4
TICA
T2
A
H
FF 5
D
Z
100:1
FIX REC
TI
710
REF
TIBA
GND
TICA
A
H
FF 6
D
N
LED
GND
A
H
FF 7
D
GND
4.7V
TIBA
SA

Table 8

Circuit Checkpoints After Clearing and Before Start of Trial

Condition	Circuit Point													
	A[a]	K	H	U	D	J	F	P	L	X	T	M	Z	N
Clear														
S off fixation	+	0	0	0	0	+	12VDC	+	0	0	0	0	0	0
Clear														
S on fixation														
No light FB[b]	+	0	0	0	0	+	12VDC	+	0	0	0	+	0	0
Clear														
S on fixation														
Light FB	+	0	0	0	0	+	12VDC	+	0	0	0	+	0	+

[a] momentarily high at clear

[b] FB stands for feedback

upon fixation, switch 3 was at TIBA, switch 4 was at ground, and switch 5 was at TIBA.

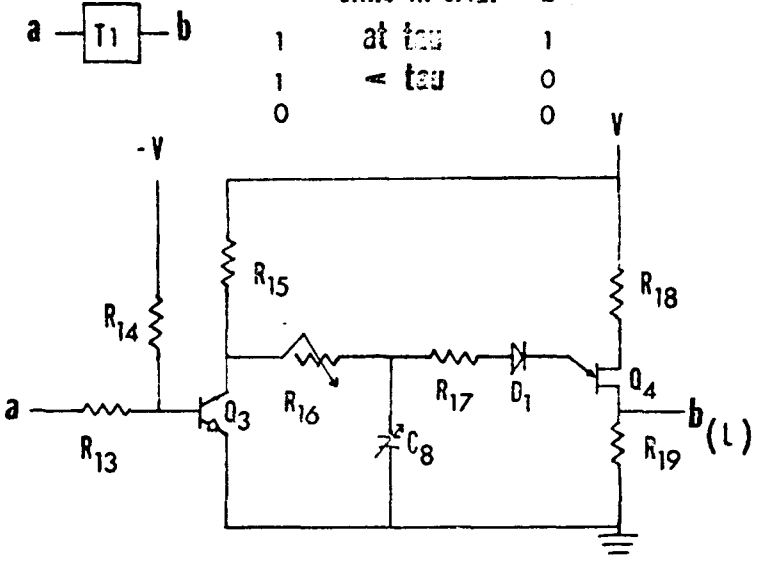
At the end of the trial (E) the Hunter timer caused point K to go high which in turn caused output J of FF_1 to go high and point P to go high. When point P was high, the D output of FF_5, FF_6, and FF_7 was low. This turned off the fixation record, the fixation spot illumination (if present) and the auditory signal (if present). The trial record recorded end of trial by a change in voltage level at point F (from 4.7 to 16.7 VDC).

Application: Stimulus presentation with constraint of visual fixation. -- Although critical visual stimuli were not presented in this experiment, the system as designed and tested provided for their presentation. Stimuli could have been presented in an unconstrained mode (i.e. independent of fixation) or in a constrained mode (i.e. contingent upon spatial and temporal criteria of fixation).

Unconstrained stimulation would have occurred if switch 1 was at H. Start of trial would cause output J of FF_3 to go low. This would cause the collector of Q_3 (Figure 16) to go high charging C_8 through $R_{15}R_{16}$. C_8 charges to a voltage necessary to turn on Q_4 which causes point L to go momentarily high. This transient high would trigger the stroboslave (General Radio Corp. Model No. 1539 A) through OR gate 5 and turn off the stimulus presentation unit through OR gate 1. The output of

Fig. 16. Schematic of unconstrained stimulus trigger timer. Circuit is conventional unijunction relaxation oscillator which is gated by a change in voltage at a (4.7 VDC to ground). The gating level may be derived from either start of trial (S-2 in Figure 15) or a programmable input (S-3 in Figure 15). Stimulus trigger (output) is not dependent upon fixation but E may mimic the constrained fixation condition by setting $R_{16}C_8$ (R_{15} being fixed) equal to the interval of fixation required in the constrained condition.

TIMER 1: UNCONSTRAINED FIXATION



OR gate 5 (point T), in addition to triggering the stimulus, would signal the trial record that a stimulus had been presented and turn off the remainder of the system through NOR gate 2.

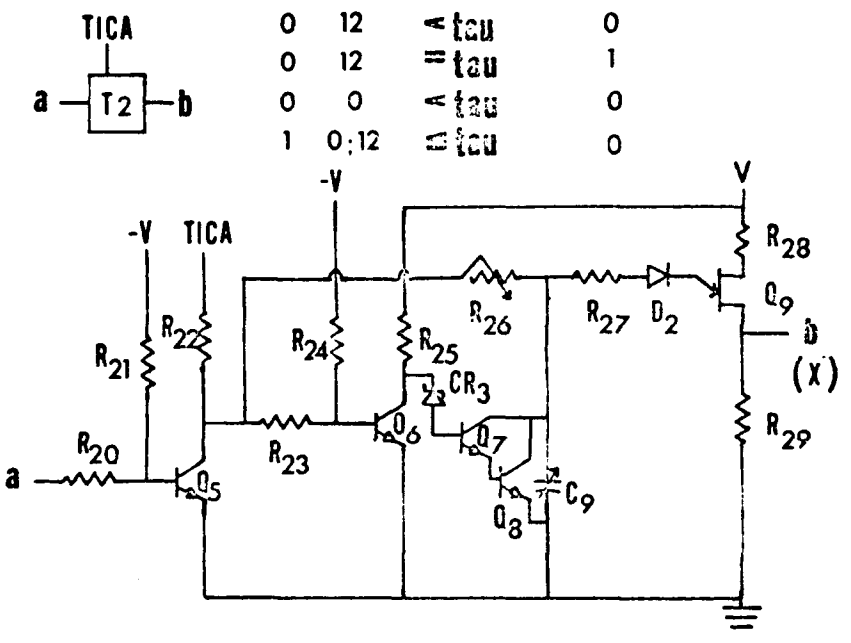
Constrained stimulation was defined to mean that O was on fixation continuously for some required duration, and that stimulus presentation was contingent upon this spatial restriction and temporal continuity. Switch 2 would have been at H causing output J of FF_4 to go low at the beginning of the trial. If output J was low, the colector of Q_5 (Figure 17) was high. The collector of Q_5 could only have been high if O in fact, were on fixation (TICA is dependent on fixation). If O was on fixation, the collector of Q_6 was low and TICA started the timer circuit of Q_9. If O remained on fixation for tau msec., output X went momentarily high, resulting in stimulus presentation through OR gate 5. The output of OR gate 5 (point T) turned off the fixation record, the fixation light (if present) and the auditory signal (if present). X turned off the stimulus presentation system through OR gate 3.

If O interrupted fixation before tau msec., the base of Q_6 went low, and the collector of Q_6 wen high. If the collector of Q_6 was high, the base of Q_7 was high and the collector of Q_7 was low. When the collector of Q_7 was low, C_9 was discharged through Q_8 to ground and held there until O

Fig. 17. Schematic of constrained fixation stimulus trigger timer. Input (a) is at ground when the trial is in progress; thus if O is on fixation, the point marked TICA (transducer input current amplifier) will be high and C_9 will charge. If O is on fixation continuously for tau, then output (b) goes momentarily high. If O interrupts fixation before tau, C_9 is discharged through Q_8 and held at ground until O returns to fixation. Discharging C_9 through Q_8 keeps b at ground, thus preventing stimulus exposure unless O is on fixation continuously for tau sec..

TIMER 2 : CONSTRAINED FIXATION

a	tica duration	tica	b
0	12	< tau	0
0	12	= tau	1
0	0	< tau	0
1	0;12	≤ tau	0



returned to fixation (i.e. until TICA was high). Thus, when O moved his gaze beyond the limits of fixation, he recycled the fixation timer to zero. The timer did not begin counting time again until O returned his gaze to the fixation area. Consequently, it would have been possible to present stimuli contingent upon spatial and temporal constraint of fixation.

A programmable input was provided for both stimulus presentation modes. This allows E to delay stimulation for some specified duration after start of trial.

Table 9

Integrated Circuit Numbers

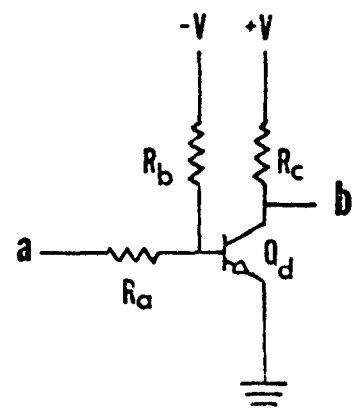
Function	I.C. Number
OR	MC 3003
NOR	SN 7402
AND	SN 7408
Inverting Amplifier	SN 7404
Flip-Flop	SN 7402[a]
Voltage Comparator	SN 72710c

[a]two latched

Fig. 18. Inverting amplifier and truth table. Integrated circuit number is specified in Table 9 and components for discrete-component amplifiers are given in Table 10.

INVERTING AMPLIFIER

$A = \overline{B}$

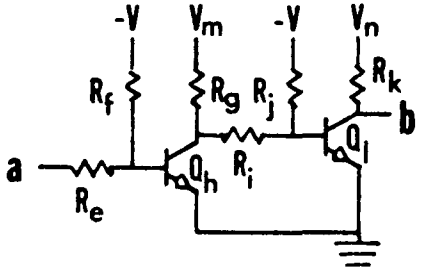


a	b
1	0
0	1

Fig. 19. Non-inverting amplifier and truth table. Integrated circuit number is specified in Table 9 and components for discrete-component amplifiers are given in Table 10.

NON-INVERTING AMPLIFIER

$A = B$



a	b
1	1
0	0

Table 10

Components for Amplifiers

Inverting Amplifiers

Amplifier No.	I.C. No.	R_a	R_b	R_c	Q_d	-V	+V
1	SN 7404						
2		390 K	3.0 M	1.0 K	2N5307	12	12
3	SN 7404						
4	SN 7404						
5		390 K	3.0 M	430Ω	2N5307	12	4.7
6	SN 7404						
7	SN 7404						
8	SN 7404						
9		390 K	3.0 M	1.0 K	2N5307	12	12
10	SN 7404						
11		200Ω	3.0 M	430Ω	2N5307	12	12

Non-Inverting Amplifiers

Amplifier No.	I.C. No.	R_e	R_f	R_g	Q_h	R_i	R_j	R_k	Q_l	-V	$+V_m$	$+V_n$
1		390 K	3.0 M	430Ω	2N5307	390 K	3.0 M	430Ω	2N5307	12	4.7	4.7
2		390 K	3.0 M	430Ω	2N5307	390 K	3.0 M	430Ω	2N5307	12	4.7	4.7
3		390 K	3.0 M	430Ω	2N5307	390 K	3.0 M	430Ω	2N5307	12	4.7	4.7
4	see comparator circuit											
5		390 K	3.0 M	1.0 K	2N5307	150 K	300 K	120Ω	2N5307	12	12	12
6		1.5 K	3.9 M	470Ω	2N5307	780 K	3.9 M	470Ω	2N5307	12	4.7	4.7
7		390 K	3.0 M	430Ω	2N5307	390 K	3.0 M	430Ω	2N5307	12	4.7	4.7

Table 11

Components for Discrete - Component Circuits

Circuit	Components	Value
Comparator and Amplifier	Comparator	SN 72710c
	R_1	1.5 K
	R_2	1.5 K
	R_3	1.0 K
	R_4	2.2 K
	R_5	1.0 K
	R_6	5.6 K
	R_7	3.3 K
	R_8	1.0 K
	R_9	5.6 K
	R_{10}	1.0 K
	R_{11}	2.0 K
	R_{12}	560 Ω
	C_1 - C_7	100 uf/50VDC
	V_1	12 VDC
	V_2	5.1 VDC
	V_3	6.2 VDC
	CR_1	1N 4733
	CR_2	1N 4735

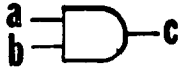
Table 11 -- Continued

Circuit	Component	Value
Comparator and		
Amplifier	Q_1	2N 3568
	Q_2	2N 3568
Unconstrained		
Fixation Timer	R_{13}	390 K
	R_{14}	3.0 M
	R_{15}	1.0 K
	R_{16}	4.5 M > R > 10 K
	R_{17}	10 Ω
	R_{18}	470 Ω
	R_{19}	100 Ω
	Q_3	2N 5307
	Q_4	2N 1671
	C_8	100 uf > C > .1 uf
	D_1	1N 5061
	-V	-12 VDC
	+V	+12 VDC
Constrained		
Fixation Timer	R_{20}	390 K
	R_{21}	3.0 M
	R_{22}	1.0 K
	R_{23}	390 K

Table 11 -- Continued

Circuit	Component	Value
Constrained		
Fixation Timer	R_{24}	3.0 M
	R_{25}	1.0 K
	R_{26}	4.5 M > R > 10 K
	R_{27}	10 Ω
	R_{28}	470 Ω
	R_{29}	68 Ω
	C_9	100 uf > C > .1 uf
	Q_5	2N 5307
	Q_6	2N 5307
	Q_7	2N 5308
	Q_8	2N 3055
	Q_9	2N 1671
	CR_3	1N 4737A
	D_2	1N 5061
	V	12 VDC
	TICA	12 VDC

Fig. 20. AND gate and truth table. Integrated circuit number is specified in Table 9.



AND GATE

AB=C

a	b	c
1	1	1
1	0	0
0	1	0
0	0	0

Fig. 21. OR gate and truth table. Integrated circuit number is specified in Table 9.

OR GATE

A+B=C

a	b	c
1	0	1
0	1	1
0	0	0
1	1	1

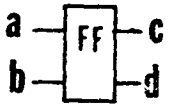
Fig. 22. NOR gate and truth table. Integrated circuit number is specified in Table 9.

NOR GATE

$A \downarrow B = \overline{C}$

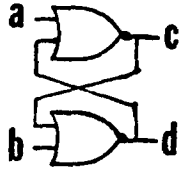
a	b	c
1	1	0
1	0	0
0	1	0
0	0	1

Fig. 23. Flip-flop and truth table. Integrated circuit number is specified in Table 9. The flip-flop is composed of two latched NOR gates.



FLIP-FLOP

a	b	c	d
1	1	0	0
0	1	1	0
1	0	0	1
0	0*	1	0
0*	0	0	1



* LAST ONE

APPENDIX II

Table 12

Total Time on Fixation During 1, 10, and 90 sec.

Fixation Intervals

Data in Seconds

Fixation Light	Sound	O	Run	Fixation Interval 1	10	90	On at Start	On at End
Off	Off	1	1	.073	1.14	1.16		
			2	1.000	3.74	22.93	Yes	
			3	.383	3.59	33.76	Yes	Yes
			4	.123	1.37	2.11		
		3	1	1.000	10.00	89.83	Yes	Yes
			2	1.000	9.83	83.24	Yes	Yes
			3	1.000	10.00	25.75	Yes	
			4	1.000	10.00	13.83	Yes	
		4	1	.762	7.51	34.96	Yes	Yes
			2	1.000	10.00	15.29	Yes	
			3	1.000	10.00	64.98	Yes	Yes
			4	1.000	3.19	11.49	Yes	Yes
Off	On	1	1	,088	1.10	24.60		Yes
			2	1.000	9.56	30.99	Yes	Yes
			3	.657	4.90	13.82	Yes	Yes
			4	.097	6.34	18.91	Yes	

Table 12 -- Continued

Fixation Light	Sound	Q	Run	Fixation Interval 1	10	90	On at Start	On at End
Off	On	3	1	0.000	0.00	0.97		
			2	.928	9.16	26.99	Yes	
			3	0.000	0.00	0.00		
			4	1.000	4.43	4.82	Yes	
		4	1	0.000	0.00	70.83		Yes
			2	0.000	0.00	4.36		
			3	0.000	4.16	51.67		Yes
			4	0.000	8.60	26.29		
Off	FB	1	1	1.000	8.50	36.59	Yes	
			2	0.000	5.21	81.57		Yes
			3	.341	6.67	83.99		Yes
			4	0.000	1.62	64.97		Yes
		3	1	0.000	6.69	85.70		Yes
			2	1.000	10.00	89.16	Yes	Yes
			3	1.000	10.00	48.23	Yes	
			4	1.000	9.80	70.45	Yes	Yes
		4	1	0.000	0.00	2.87		
			2	1.000	7.06	39.45	Yes	
			3	1.000	10.00	70.92	Yes	Yes
			4	1.000	10.00	79.19	Yes	Yes

Table 12 -- Continued

Fixation Light	Sound	O	Run	Fixation Interval 1	10	90	On at Start	On at End
On	Off	1	1	.635	3.78	54.04	Yes	
			2	.341	3.71	10.47	Yes	
			3	.951	7.98	19.43		
			4	.234	1.31	1.75	Yes	
		3	1	1.000	7.03	43.89	Yes	
			2	1.000	10.00	63.86	Yes	
			3	0.000	0.00	0.00		
			4	1.000	5.62	10.50	Yes	
		4	1	0.000	0.00	0.00		
			2	1.000	10.00	39.58	Yes	
			3	0.000	0.15	25.30		
			4	1.000	9.71	79.43	Yes	Yes
On	On	1	1	0.000	0.00	0.00		
			2	1.000	9.12	23.76	Yes	
			3	1.000	8.86	14.98	Yes	
			4	.073	0.07	0.79		
		3	1	.927	9.32	58.36	Yes	
			2	.587	1.50	46.94		Yes
			3	1.000	10.00	49.62	Yes	
			4	1.000	9.82	88.34	Yes	Yes

Table 12 -- Continued

Fixation Light	Sound	O	Run	Fixation Interval 1	10	90	On at Start	On at End
On	On	4	1	1.000	3.54	8.87	Yes	
			2	0.000	7.22	86.83	Yes	Yes
			3	.783	9.85	79.59	Yes	Yes
			4	0.000	2.53	10.02		
On	FB	1	1	0.000	0.00	0.00		
			2	.802	8.56	53.41	Yes	Yes
			3	.708	9.43	76.23	Yes	Yes
			4	.221	7.77	75.29		Yes
		3	1	1.000	9.96	88.77	Yes	Yes
			2	1.000	9.93	86.45	Yes	Yes
			3	1.000	10.00	41.79	Yes	
			4	1.000	9.90	84.32	Yes	Yes
		4	1	1.000	10.00	90.00	Yes	Yes
			2	1.000	1.78	82.42	Yes	Yes
			3	0.000	4.33	76.61		Yes
			4	.827	9.49	62.45	Yes	Yes
FB	Off	1	1	.887	8.54	77.28	Yes	Yes
			2	.584	4.59	74.42	Yes	Yes
			3	1.000	9.02	85.12	Yes	Yes
			4	0.000	0.00	57.78		Yes

Table 12 - Continued

Fixation Light	Sound	O	Run	Fixation Interval 1	10	90	On at Start	On at End
FB	Off	3	1	1.000	10.00	90.00	Yes	Yes
			2	0.000	4.93	78.40		
			3	.246	8.76	30.50	Yes	
			4	1.000	10.00	89.46	Yes	Yes
		4	1	1.000	10.00	44.02	Yes	
			2	1.000	9.93	89.70	Yes	Yes
			3	1.000	10.00	81.46	Yes	Yes
			4	1.000	10.00	82.22	Yes	Yes
FB	On	1	1	.912	8.75	83.53	Yes	
			2	1.000	9.06	79.34	Yes	Yes
			3	.878	7.90	82.59		Yes
			4	1.000	5.20	77.79		Yes
		3	1	1.000	10.00	80.63	Yes	Yes
			2	1.000	9.56	89.11	Yes	Yes
			3	1.000	9.72	86.06	Yes	Yes
			4	.522	8.79	57.49		
		4	1	1.000	9.95	67.52	Yes	Yes
			2	0.000	0.00	0.00		
			3	1.000	10.00	84.14	Yes	Yes
			4	0.000	6.60	66.40		Yes

Table 12 -- Continued

Fixation Light	Sound	O	Run	Fixation Interval 1	10	90	On at Start	On at End
FB	FB	1	1	.778	8.97	75.03	Yes	
			2	.768	9.55	78.92	Yes	Yes
			3	.810	9.41	83.37	Yes	Yes
			4	0.000	3.07	74.74		Yes
		3	1	1.000	9.89	68.53	Yes	Yes
			2	1.000	9.68	87.67	Yes	Yes
			3	1.000	10.00	88.86	Yes	Yes
			4	1.000	10.00	87.03	Yes	Yes
		4	1	1.000	7.18	7.24	Yes	
			2	1.000	10.00	89.16	Yes	Yes
			3	1.000	9.37	84.22	Yes	Yes
			4	1.000	9.37	61.10	Yes	Yes

Note. -- O_2 was eliminated from the experiment because his uncorrected Snellen score did not meet the 20/20 requirement previously decided upon.

Fig. 24. Cumulative fixation duration as a function of time in trial. $\underline{0}_1$: unilluminated target, no auditory signal.

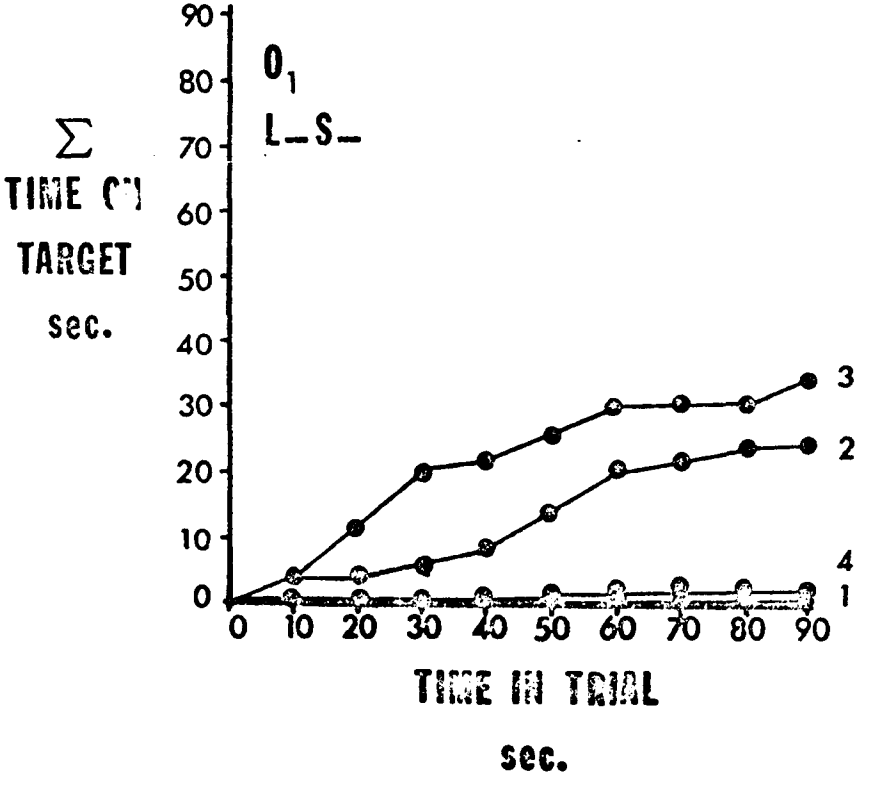

O_1
L—S—
Σ
TIME (')
TARGET
sec.
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.
3
2
4
1

Fig. 25. Cumulative fixation duration as a function of time in trial. $\underline{O}_1$: unilluminated target, continuous auditory signal.

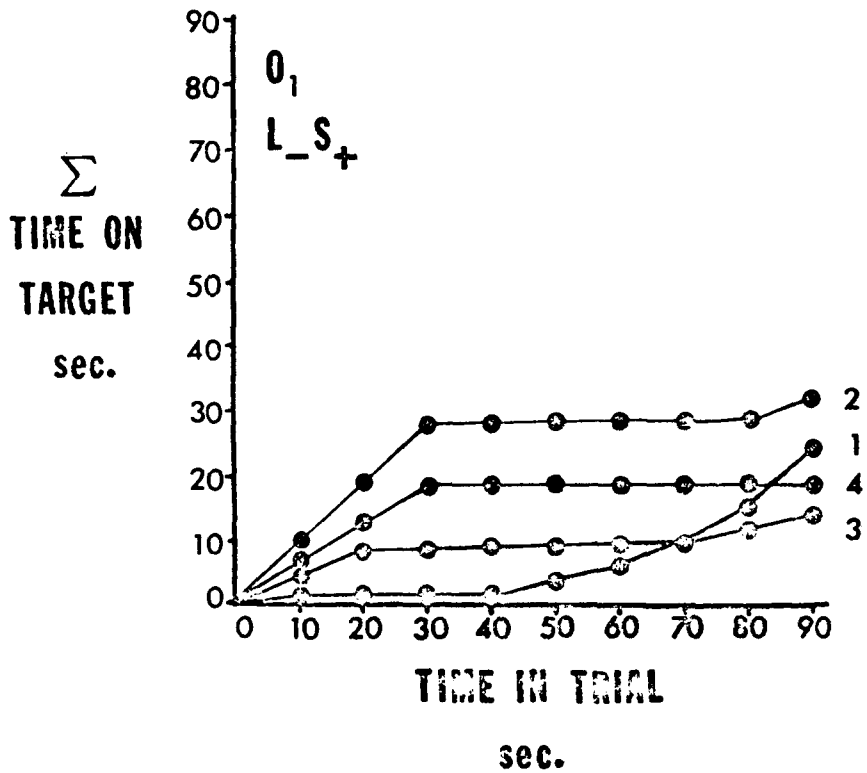

90
80
70
60
50
40
30
20
10
0
O_1
L_S_+
Σ
TIME ON
TARGET
sec.
2
1
4
3
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.

Fig. 26. Cumulative fixation duration as a function of time in trial. $\underline{O}_1$: unilluminated target, feedback auditory signal.

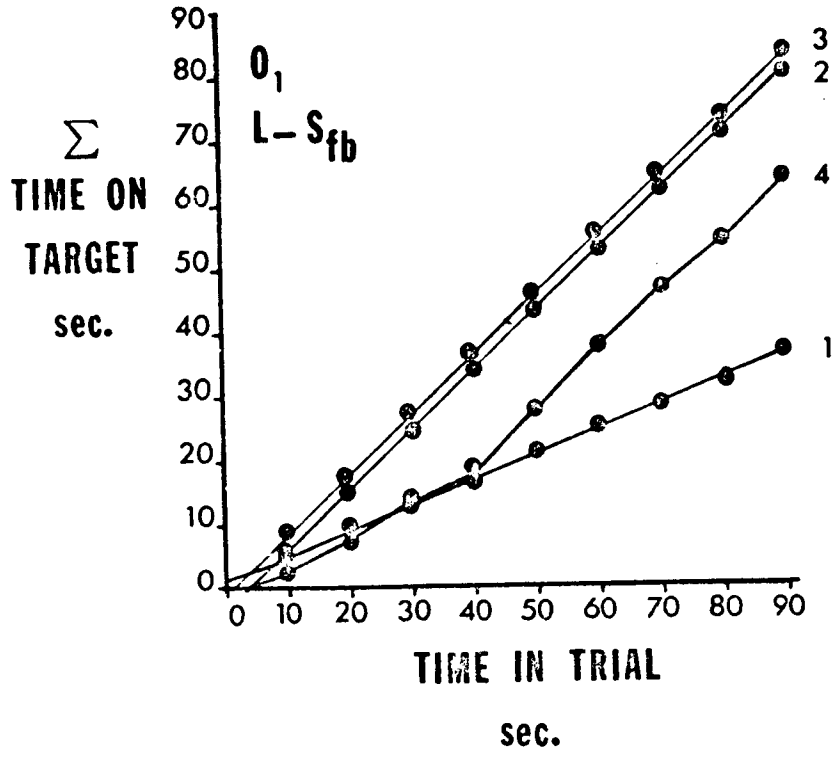

O_1
$L - S_{fb}$
Σ TIME ON TARGET sec.
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL sec.
3
2
4
1

Fig. 27. Cumulative fixation duration as a function of time in trial. $\frac{0}{1}$: illuminated target, no auditory signal.

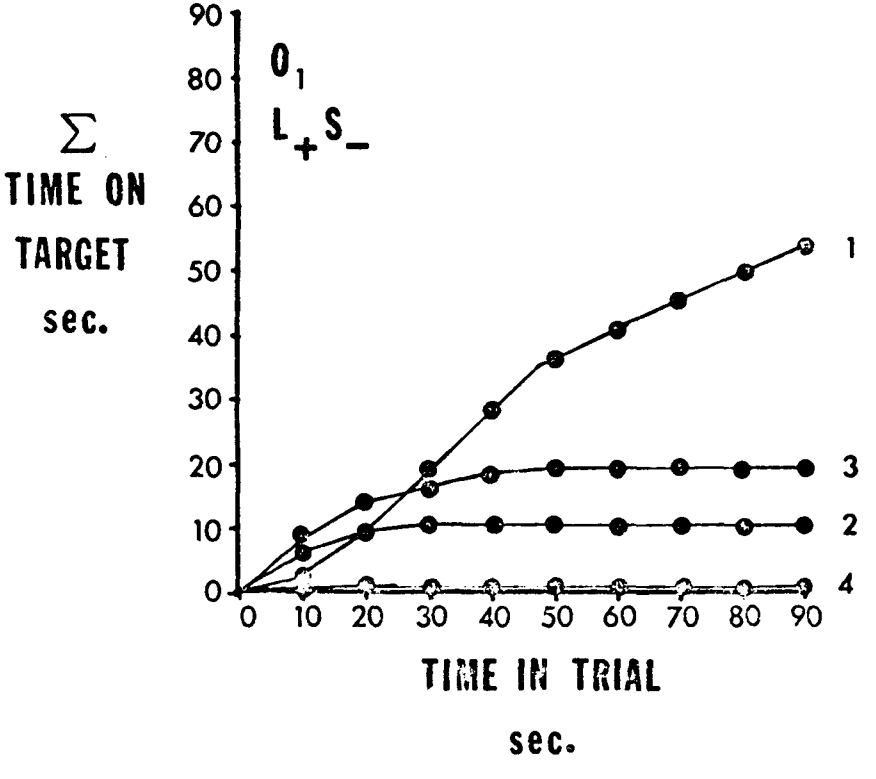

90
80
70
60
50
40
30
20
10
0
O_1
L_+S_-
Σ
TIME ON
TARGET
sec.
1
3
2
4
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.

Fig. 28. Cumulative fixation duration as a function of time in trial. $\underline{O}_1$: illuminated target, continuous auditory signal.

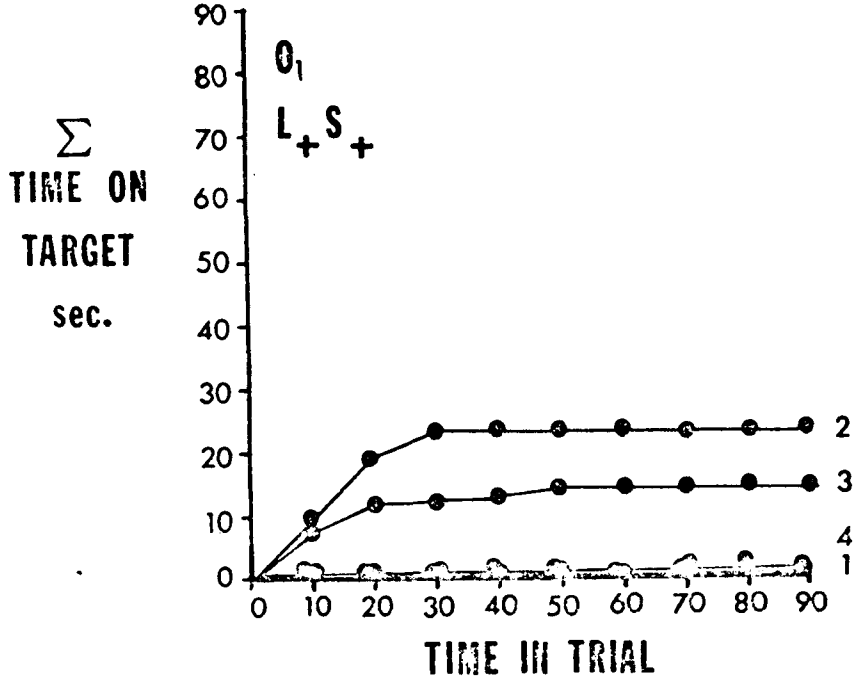

90
80
70
60
50
40
30
20
10
0
O_1
L_+S_+
Σ
TIME ON
TARGET
sec.
2
3
4
1
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.

Fig. 29. Cumulative fixation duration as a function of time in trial. $\underline{O}_1$: illuminated target, feedback auditory signal.

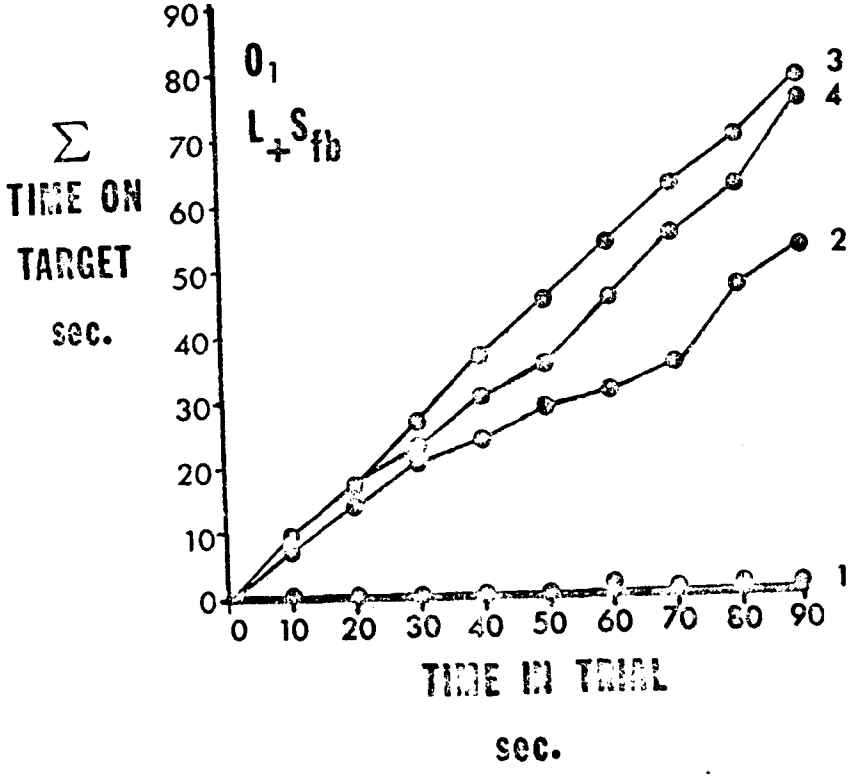

90
80
70
60
50
40
30
20
10
0
O_1
L_+S_{fb}
Σ
TIME ON
TARGET
sec.
3
4
2
1
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.

Fig. 30. Cumulative fixation duration as a function of time in trial. $\underline{O}_1$: feedback target, no auditory signal.

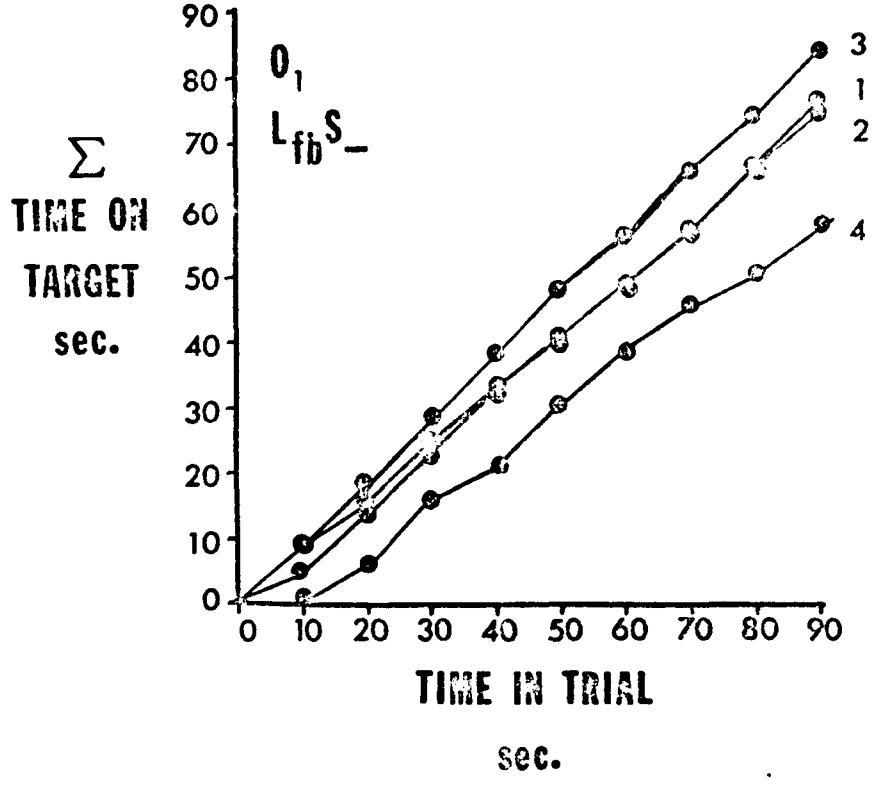

O_1
$L_{fb}S_-$
Σ TIME ON TARGET sec.
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL sec.
3
1
2
4

Fig. 31. Cumulative fixation duration as a function of time in trial. $\underline{O}_1$: feedback target, continuous auditory signal.

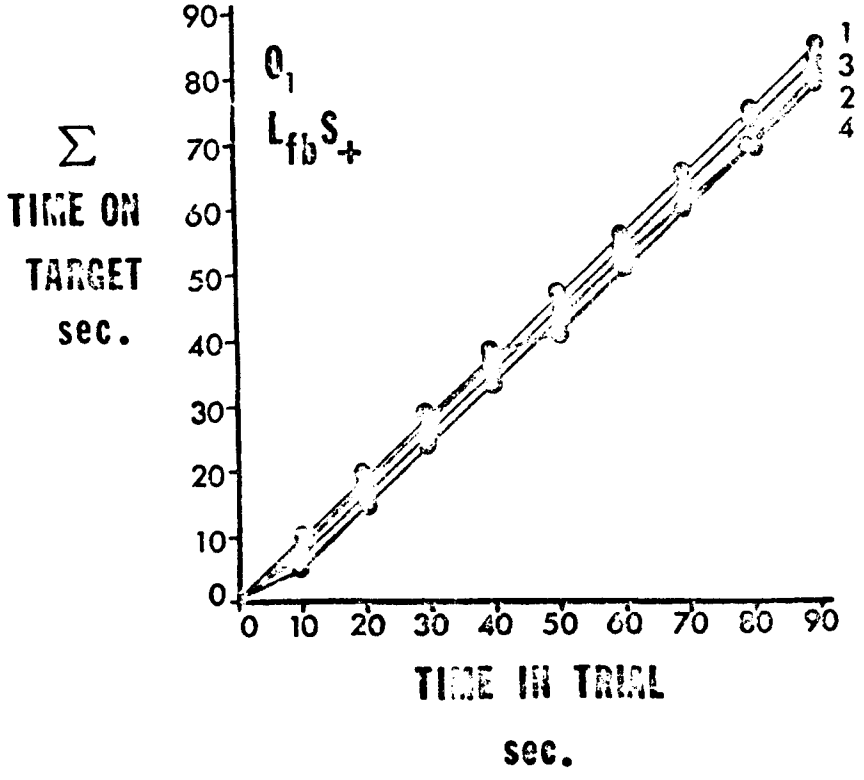

Σ
TIME ON
TARGET
sec.
90
80
70
60
50
40
30
20
10
0
O_1
$L_{fb}S_+$
1
3
2
4
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.

Fig. 32. Cumulative fixation duration as a function of time in trial. $\underline{O}_3$: unilluminated target, no auditory signal.

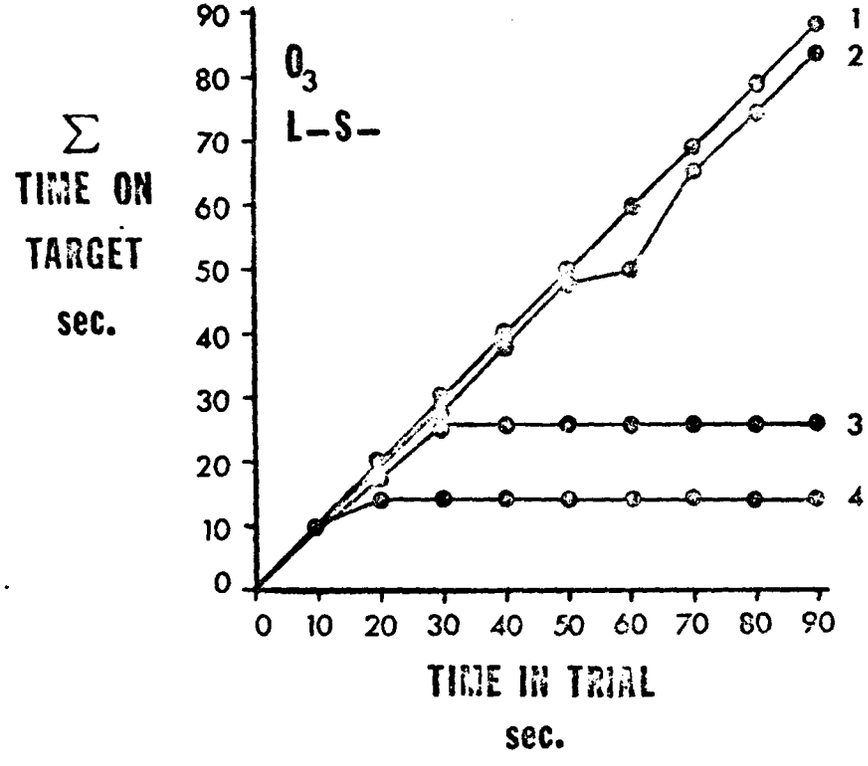

Σ
TIME ON
TARGET
sec.
O_3
L–S–
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.
1
2
3
4

Fig. 33. Cumulative fixation duration as a function of time in trial. $\underline{0}_3$: unilluminated target, continuous auditory signal.

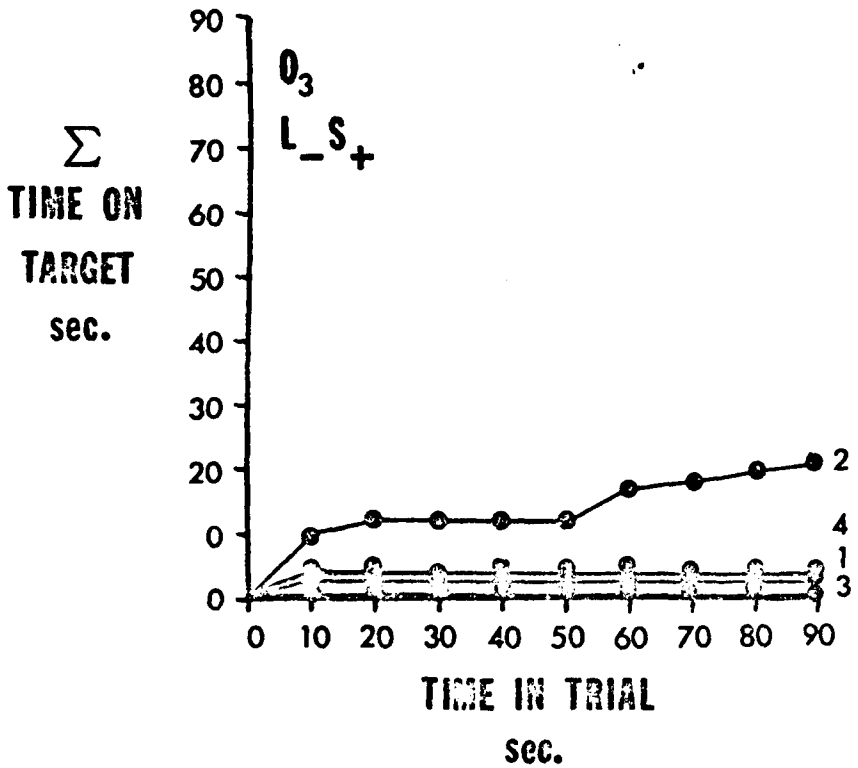

Σ
TIME ON
TARGET
sec.
90
80
70
60
50
40
30
20
0
0
O_3
L_S_+
2
4
1
3
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.

Fig. 34. Cumulative fixation duration as a function of time in trial. $\underline{O}_3$: unilluminated target, feedback auditory signal.

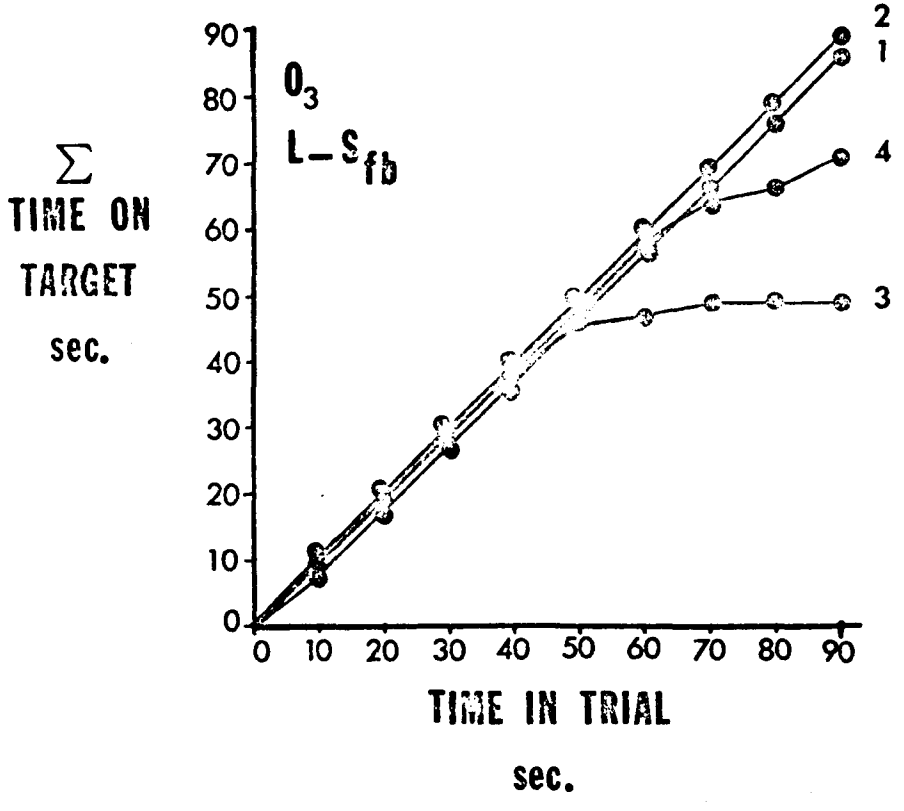

Σ
TIME ON
TARGET
sec.
90
80
70
60
50
40
30
20
10
0
O_3
$L-S_{fb}$
2
1
4
3
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.

Fig. 35. Cumulative fixation duration as a function of time in trial. $\underline{O}_3$: illuminated target, no auditory signal.

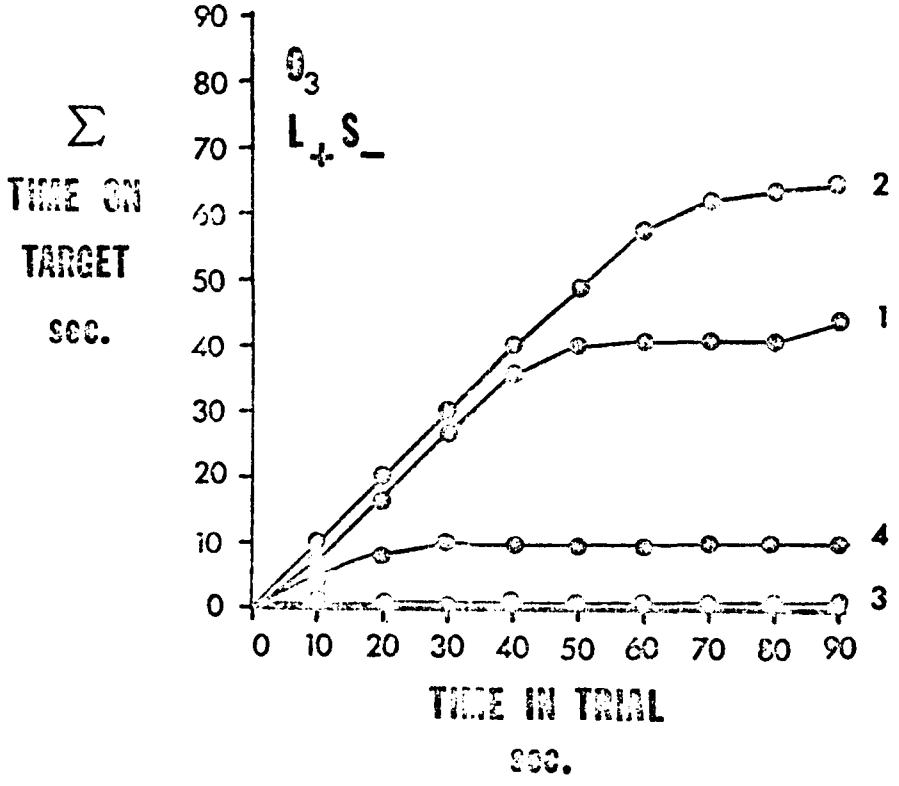

Σ
TIME ON
TARGET
sec.
90
80
70
60
50
40
30
20
10
0
θ_3
$L_+ S_-$
2
1
4
3
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.

Fig. 36. Cumulative fixation duration as a function of time in trial. $\underline{O}_3$: illuminated target, continuous auditory signal.

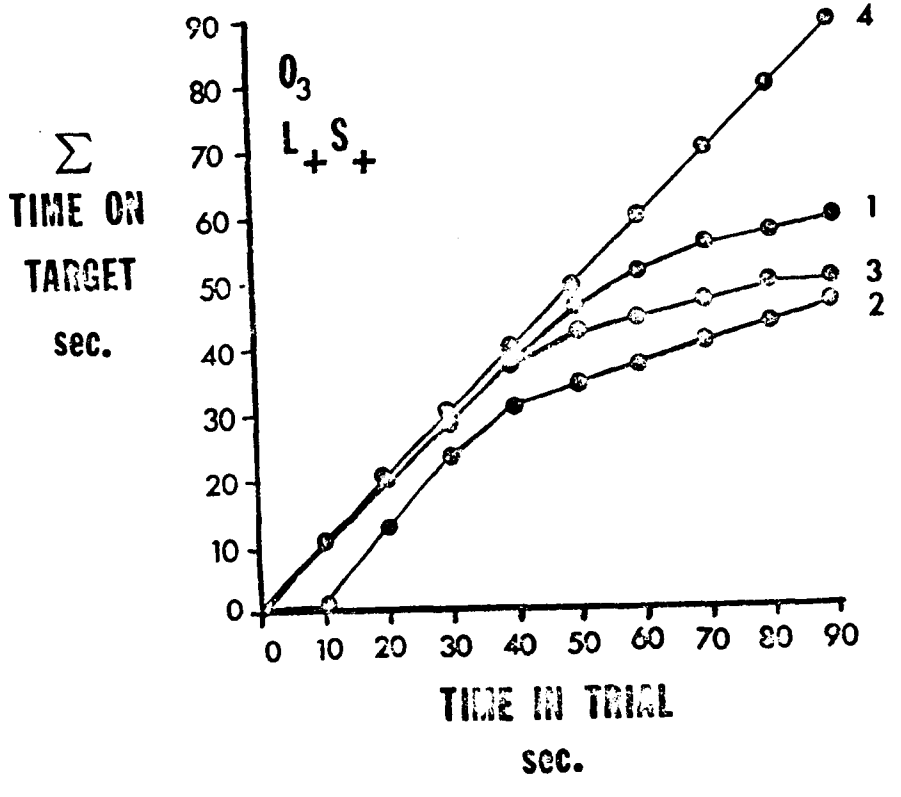

Σ
TIME ON
TARGET
sec.
90
80
70
60
50
40
30
20
10
0
O_3
L_+S_+
4
1
3
2
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.

Fig. 37. Cumulative fixation duration as a function of time in trial. $\underline{O}_3$: illuminated target, feedback auditory signal.

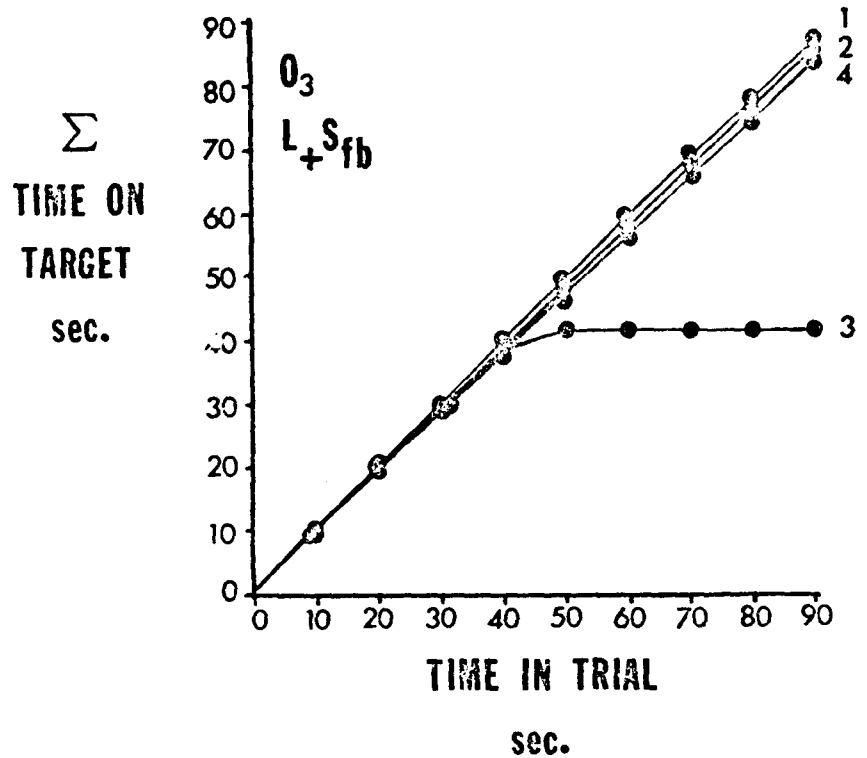

Σ
TIME ON
TARGET
sec.
O_3
L_+S_{fb}
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.
1
2
4
3

Fig. 38. Cumulative fixation duration as a function of time in trial. $\underline{O}_3$: feedback target, no auditory signal.

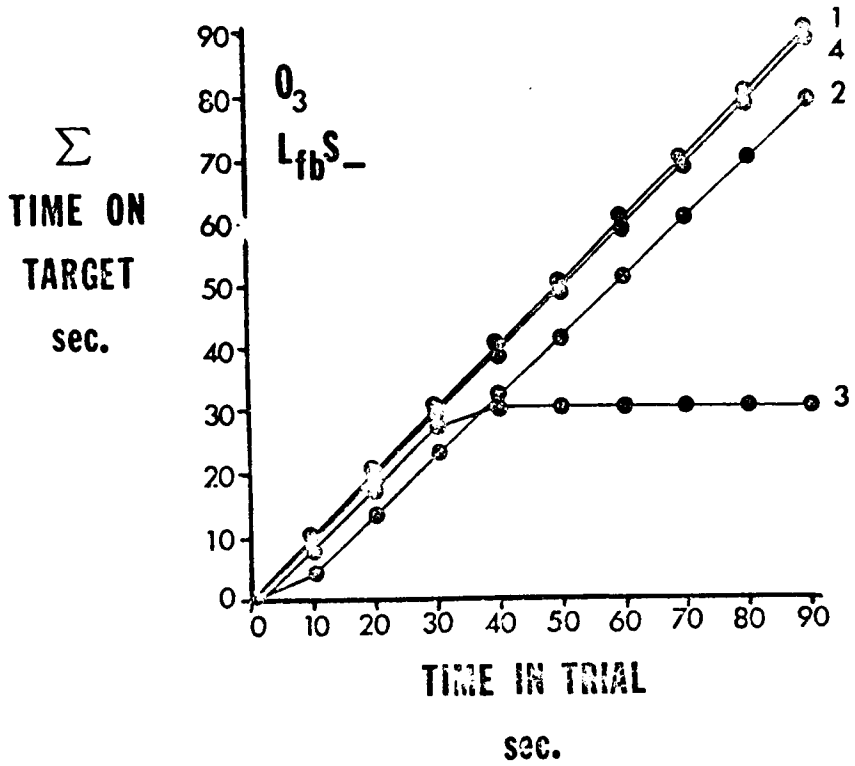

Σ
TIME ON
TARGET
sec.
90
80
70
60
50
40
30
20
10
0
O_3
$L_{fb}S_-$
1
4
2
3
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.

Fig. 39. Cumulative fixation duration as a function of time in trial. $\underline{O}_3$: feedback target, continuous auditory signal.

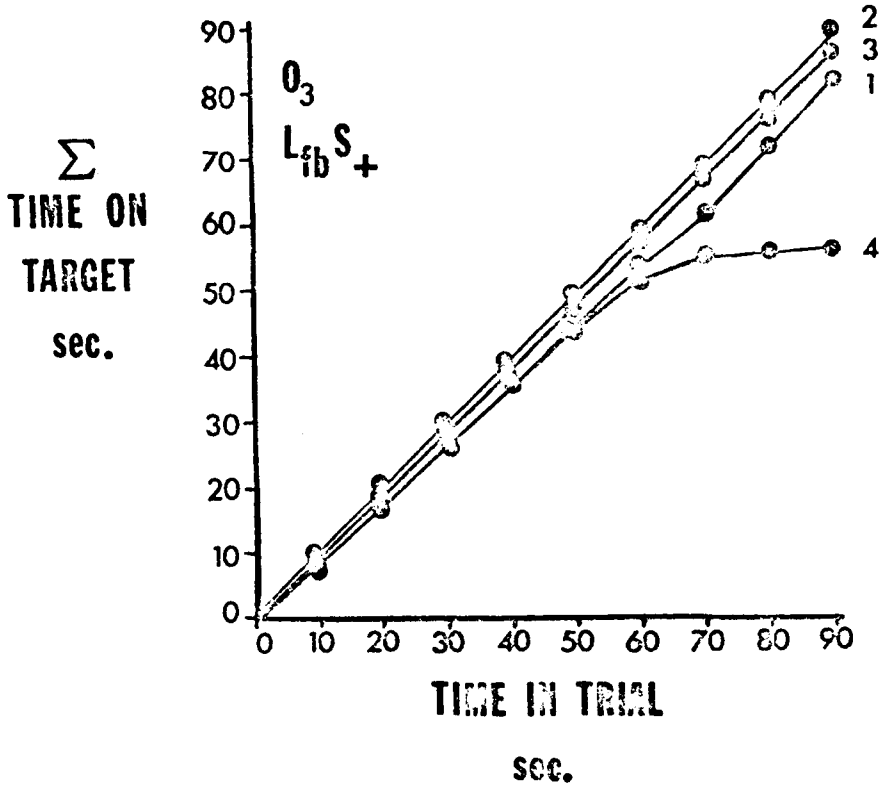

Σ
TIME ON
TARGET
sec.
90
80
70
60
50
40
30
20
10
0
O_3
$L_{fb}S_+$
2
3
1
4
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.

Fig. 40. Cumulative fixation duration as a function of time in trial. $\underline{O}_4$: unilluminated target, no auditory signal.

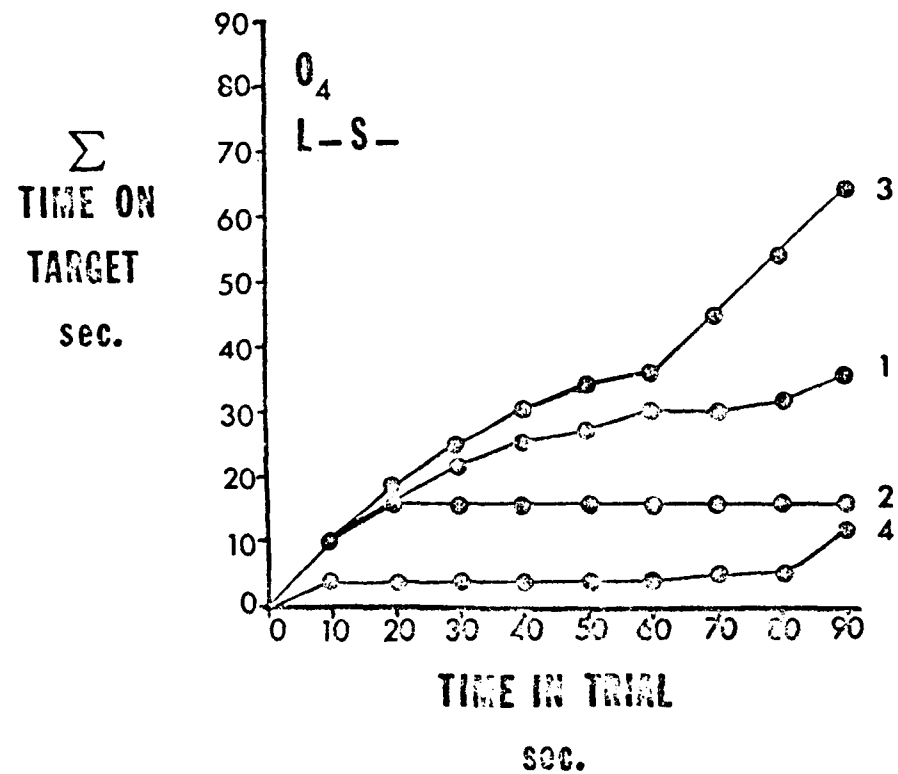

O_4
L–S–
Σ TIME ON TARGET sec.
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL sec.
3
1
2
4

Fig. 41. Cumulative fixation duration as a function of time in trial. $\underline{O}_4$: unilluminated target, continuous auditory signal.

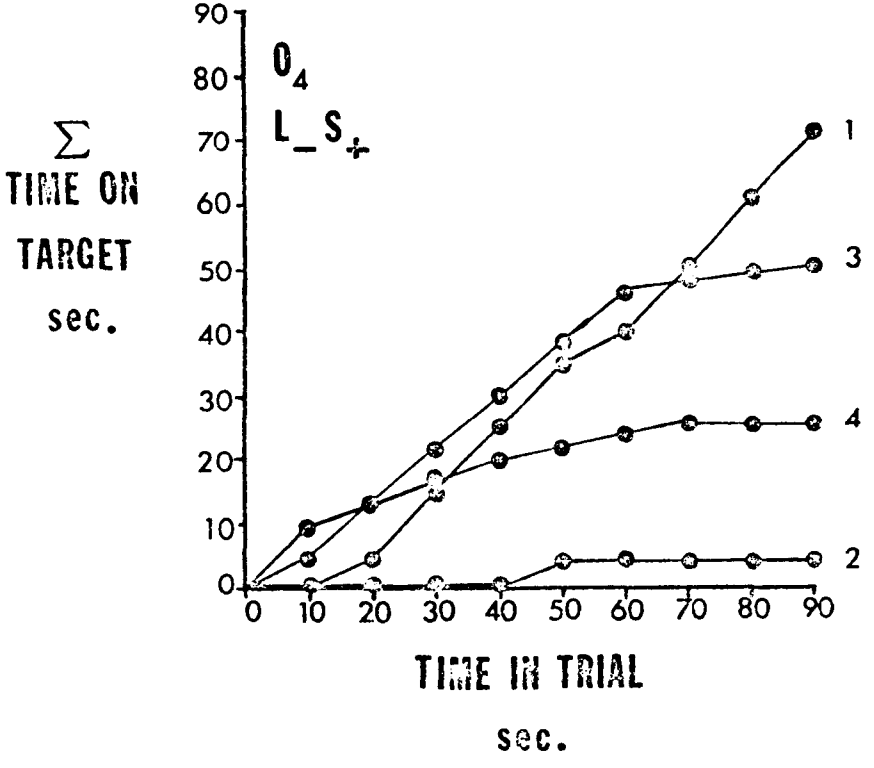

O_4
L_S_+
Σ TIME ON TARGET sec.
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL sec.
1
3
4
2

Fig. 42. Cumulative fixation duration as a function of time in trial. $\underline{O}_4$: unilluminated target, feedback auditory signal.

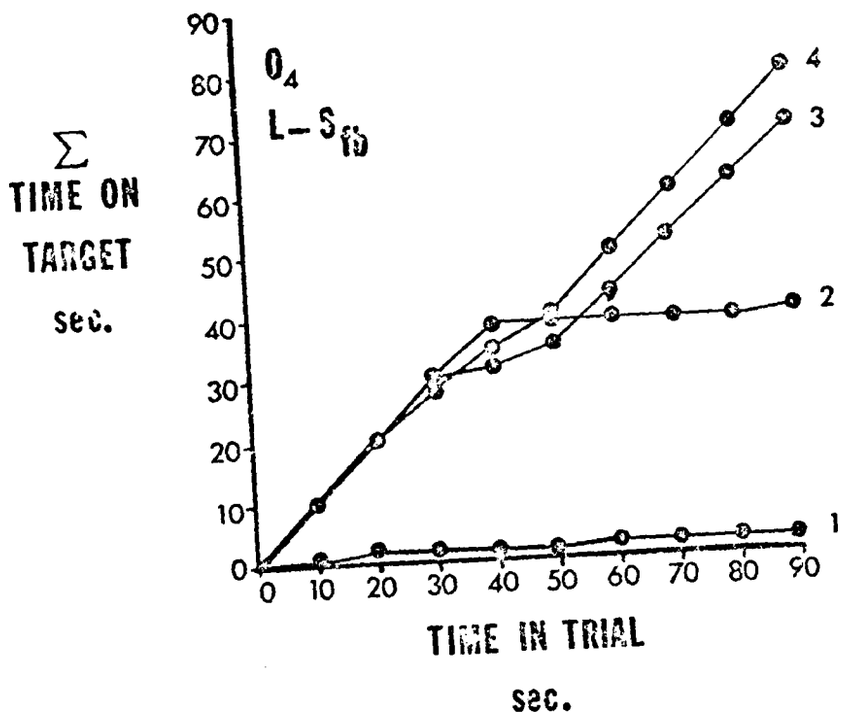

Σ
TIME ON
TARGET
sec.
O_4
L – S_{fb}
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.
1
2
3
4

Fig. 43. Cumulative fixation duration as a function of time in trial. $\frac{0}{4}$: illuminated target, no auditory signal.

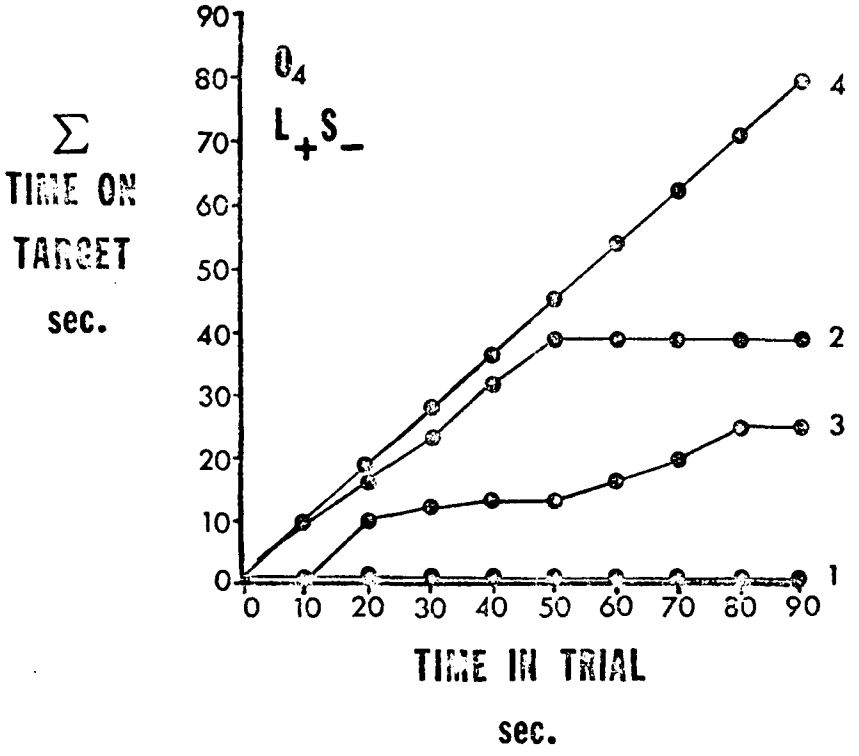

Σ
TIME ON
TARGET
sec.
O_4
L_+S_-
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90
4
2
3
1
TIME IN TRIAL
sec.

Fig.44 . Cumulative fixation duration as a function of time in trial. $\underline{O}_4$: illuminated target, continuous auditory signal.

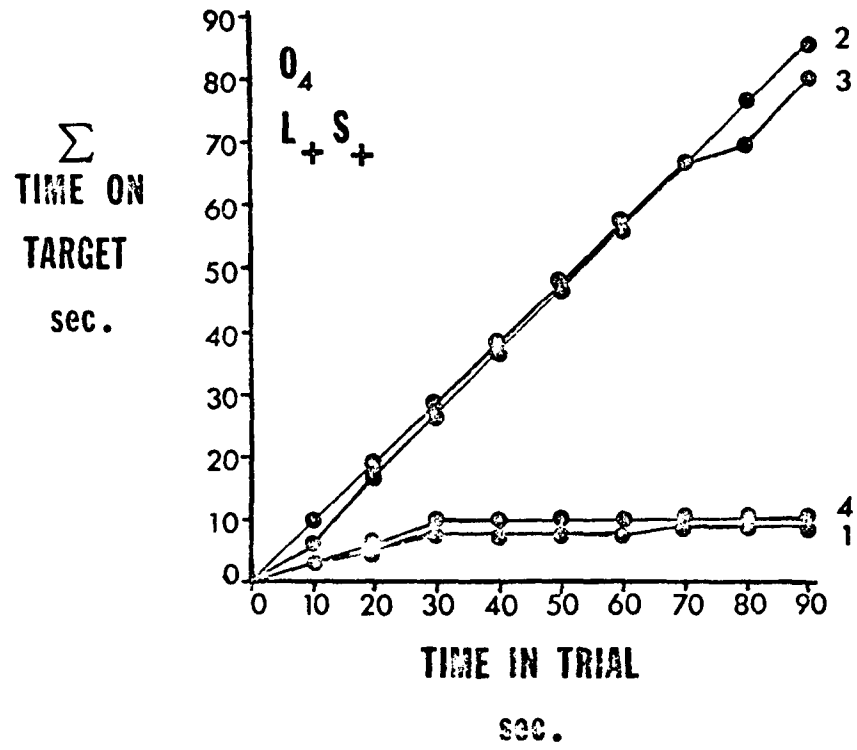

Σ
TIME ON
TARGET
sec.
O_4
$L_+ S_+$
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.
2
3
4
1

Fig. 45. Cumulative fixation duration as a function of time in trial. O_4: illuminated target, feedback auditory signal.

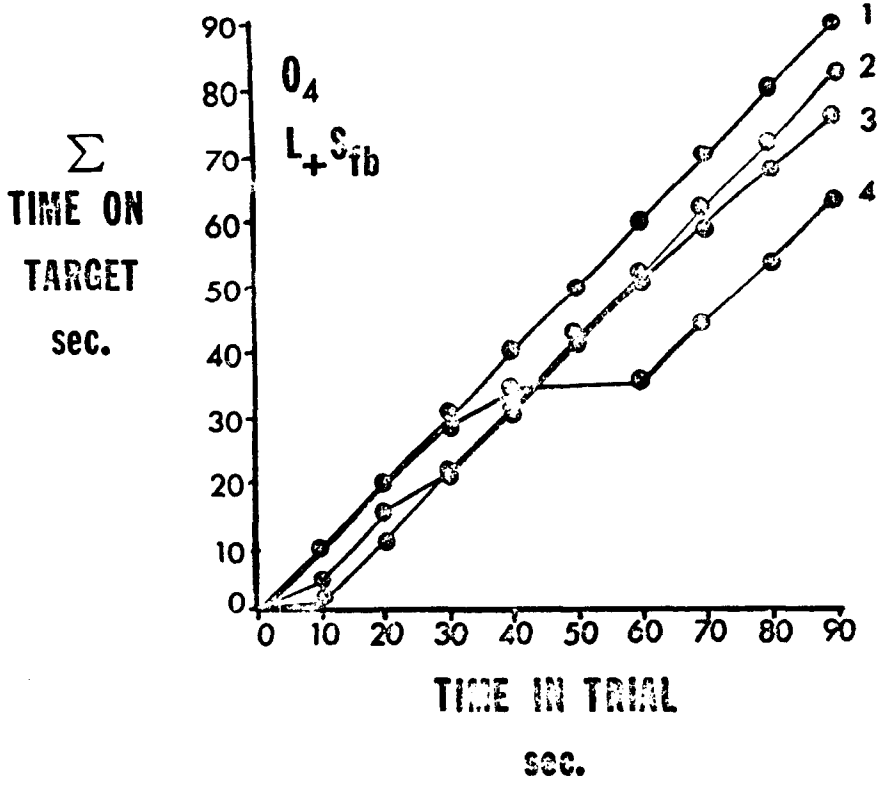

Σ
TIME ON
TARGET
sec.
90
80
70
60
50
40
30
20
10
0
O_4
$L_+ S_{fb}$
1
2
3
4
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.

Fig. 46. Cumulative fixation duration as a function of time in trial. $\underline{O}_4$: feedback target, no auditory signal.

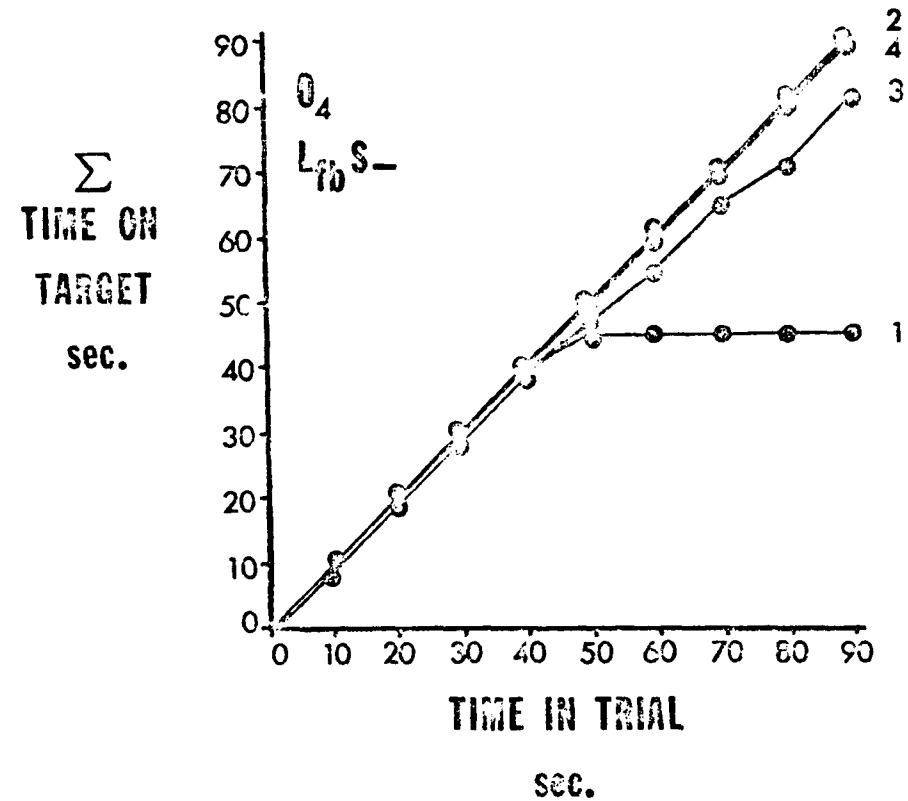
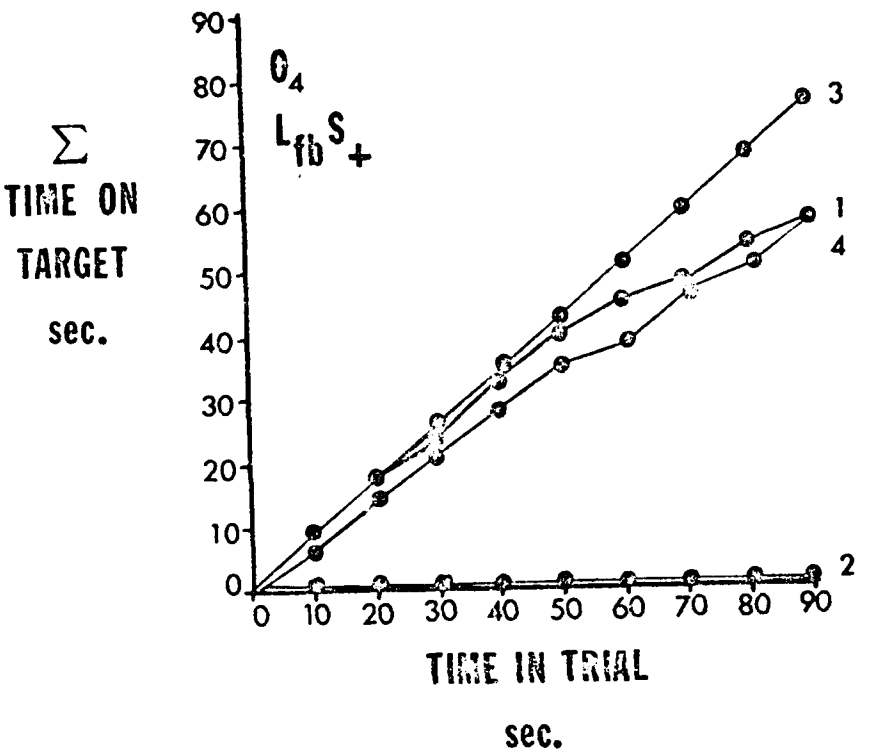

Σ
TIME ON
TARGET
sec.
90
80
70
60
50
40
30
20
10
0
O_4
$L_{7b}S-$
2
4
3
1
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.

Fig. 47. Cumulative fixation duration as a function of time in trial. $\underline{O}_4$: feedback target, continuous auditory signal.


Σ
TIME ON
TARGET
sec.
O_4
$L_{fb}S_+$
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90
TIME IN TRIAL
sec.
1
2
3
4

AUTOBIOGRAPHICAL STATEMENT

I was born in New York City on March 31, 1943, and was raised in Elmont, New York, where I graduated from Elmont Memorial High School (June, 1960). I received a B. A. from the University of Vermont (June, 1964) and an M.A. from Mount Holyoke College (November, 1965; Biological Sciences). I then attended Yeshiva University and Hofstra University, the latter as a visiting student. I have been awarded the following scholarships and fellowships: University of Vermont New York City Alumni Scholarship, Elks Scholarship, Kiwanis Scholarship, National Science Foundation Undergraduate Research Participant, Departmental Assistant (Biological Sciences, Mount Holyoke College), Research Assistant (Educational Psychology, Yeshiva University), United States Public Health Service Trainee in Physiological Psychology (Queens College), National Institute of Mental Health Predoctoral Research Fellowship (Queens College), City University of New York Dissertation Fellowship (Queens College).

I have been employed as a Fellow in Neurology at the Mount Sinai School of Medicine, (1971-) as an Assistant Professor (P/T) of Psychology at St. Francis College (1972), as an instructor of phychology in the summer session at Queens College (1970, 1971), as a Lecturer in Psychology (P/T) at Queens College, (1970-1971), and as an Instructor of Psychology in the Evening Division at

C.W. Post College (1968-1969). I have also served as a research assistant in the Department of Neurosurgery at Brooklyn Jewish Hospital (1967) and in the Laboratory of Biophysics of the National Institutes of Health in Woods Hole, Mass., (1966). I am a graduate of the NASA/Univ. Va. Bio Space Technology Training Program (1968) and the College Junior Course VII, United States Women's Army Corps School, Ft. McClellan, Alabama (1963). I have been a Library Investigator at the Marine Biological Laboratory at Woods Hole, Mass., (1969).

I am a member of the Society of the Sigma Xi (March, 1970), The New York Academy of Sciences (October, 1968), Psi Chi (November, 1968), the Eastern Psychological Association (1967), and the American Association for the Advancement of Science. I am an associate of the American Psychological Association.

I have presented papers at the Mount Holyoke Undergraduate Psychology Conference (May, 1964), and the Eastern Psychological Association (April, 1965 and April, 1967). I have an invention report on file with the Office of the Surgeon General (May, 1968).

My extra-curricular activities include: Student Representative, the Executive Committee in Psychology, CUNY; Corresponding Secretary, FDR Democratic Club, Nassau County; Varsity Debator, University of Vermont; International Area Chairman and 1st Vice President, B'nai Brith Girls; Chairman of the Board, the University Center, University of Vermont.