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DEVELOPMENT AND EVALUATION OF A PERFORMANCE-BASED TEST OF SACCADIC AND VESTIBULO-OCULAR CONTROL

Lynn C. Percival and Fred E. Guedry, Jr.

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NAVAL AEROSPACE MEDICAL RESEARCH LABORATORY
PENSACOLA FLORIDA

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Naval Medical Research and Development Command
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SUMMARY PAGE

THE PROBLEM

To acquire visual information from spatially separated points, the oculomotor control systems are called upon to shift and then stabilize gaze or line of sight relative to a target. Though the demand for efficient function exists in normal environments, it is perhaps much greater in aviation with its time pressures and spatially distributed information. Gaze shifts requiring head and eye movement involve vestibular as well as other oculomotor control systems. The purpose of the present study was to develop and evaluate an initial version of a performance-based test of gaze control which will be sensitive to normal individual differences and also to certain central nervous system and vestibular pathology and which will be less equipment, personnel and time intensive than tests currently in use. The procedure developed uses performance to establish initial gaze position and to insure that the required shift and stabilization of gaze are rapidly produced. The time of exposure of visual stimuli is limited so that relatively great demands are placed on the oculomotor control systems.

FINDINGS

Performance in three experiments was consistently and powerfully influenced by exposure time, and to a lesser extent by the size of the required gaze shift. Wider inter-character spacing of the visual stimulus resulted in a small, but significant improvement in performance when eye, or coordinated head and eye movement was required. A multiple regression equation involving exposure time, gaze shift size and spacing accounted for over 82% of the total variance; more than 65% was accounted for by exposure time with most of the remaining due to gaze shift size. The results have implications in three areas. 1) Because of the powerful influence of exposure time on performance it is suggested that the test will be sensitive to certain types of CNS and vestibular pathology; these pathological conditions will act to reduce the time that the visual stimulus is seen by the subject. 2) Variation in performance across subjects suggests that the test may be sensitive to individual differences in oculomotor abilities, although some modification to make it more demanding may be required. 3) The effect of inter-character spacing on performance at levels above the current required minimum suggests that the military standards for thin, bright characters may need to be re-evaluated. A recommended version of the test is fully described.

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INTRODUCTION

The function of the oculomotor control system is to position the eyes so that visual information may be obtained from the environment. Vergence, pursuit and saccadic movements are required as well as stabilization of the eyes relative to a target while the head is in motion. The systems which are involved in a rapid shift in line of sight, or gaze, to a target, followed by ocular stabilization on the target are of particular interest in the present study because of their role in military aviation. In that environment with its time pressures and spatially distributed visual information, the ability to produce quick accurate shifts in gaze followed by rapid retinal image stabilization is required to obtain necessary visual information. A simple test might 1) identify differences in ability between normal individuals which affect limits of visual scan and 2) serve as a diagnostic screen for pathology of the control systems involved. It might also provide additional human engineering data for use in performance estimation or equipment standards.

Several procedures have been developed to assess normal and abnormal functioning of the physiological systems involved in oculomotor control. A short description of the procedures is presented in Table I. They yield qualitative and quantitative information of use in the development and evaluation of models of oculomotor control systems and in the clinical diagnosis of labyrinthine and certain types of CNS pathology. For these purposes the procedures listed provide the most detailed information currently available; however, they also require large committments of equipment and technical personnel to administer and time for data collection and analysis. Other, simpler procedures have been developed but they require administration by a skilled and experienced clinician (33).

The purpose of the present study was to develop and evaluate an initial version of a performance test which, when implemented, will potentially be sensitive to normal individual differences and to certain types of central nervous system (CNS) and vestibular pathology, and which will be less equipment, personnel and time intensive than the tests in Table I. The test is not meant to replace procedures of that table but rather is meant to provide a simpler, quicker method of testing oculomotor control. It is based on the assumption that one major function of the oculomotor control system is to provide a stable foveal image of an object during head movement for the purpose of the extraction of information. The rationale for the test then is to use the quantity of information extracted within a short time interval immediately following a gaze shift as a measure of oculomotor efficiency. The ability to quickly and accurately shift gaze and stabilize the retinal image will produce a high level of performance, while slow and/or inaccurate shifts or failure to stabilize will result in a low level of performance.

This ability is under constant demand in everyday life, but it is perhaps most crucial in the aerospace community. The pilot of a modern aircraft must perform numerous tasks requiring visual data retrieval inside as well as outside the cockpit. One of the most important tasks is visual scan of the cockpit instruments to obtain information necessary for flying the aircraft and successfully performing the mission. In scanning, the pilot repeatedly shifts gaze then briefly "locks on" to various displays to acquire information. The test procedure under development requires this kind of performance. If the necessary relationship between time and performance can be established and if the procedure is sensitive to individual differences it may be a useful pilot selection and testing device. Of course test performance should bear some meaningful relationship to more extensive measures of visual scan performance in aviation (26).

TABLE I

Selected Methods for Oculomotor Control Systems Evaluation

Method	Description	Measures	Reference
1	A single saccadic eye movement with head fixed, to acquire a target displaced 40° or less from some fixation point.	Saccade latency, velocity, peak velocity, duration and accuracy.	24
2	A single coordinated head and eye movement to acquire a target displaced 30-120° from some fixation point.	Saccade and head movement latency, velocity, peak velocity and duration. Gaze accuracy and stability following shift to the target.	1
3	Head oscillation at various frequencies through an angle of ± 20° while maintaining fixation on an earth- or head-fixed target.	Gain (ratio of peak eye-to-head velocity), eye-head phase differences, eye-head velocity functional relationship (e.g., linear, cubic).	32
4	Passive whole body rotation using different waveforms, peak velocities, etc., in the dark and while maintaining fixation on a head-fixed target.	Nystagmus slow phase velocity, suppression (slow phase velocity in dark vs. head-fixed target), visual performance during nystagmus.	7

Clinical eye movement research using Method 1 of Table I demonstrates that patients with several types of CNS disorders will display saccadic dysmetria, low velocity saccades or both (15,25,27). The dysmetria may involve undershooting and/or overshooting; in some disorders multiple step hypometric saccades occur. In contrast normal subjects produce high velocity saccades with fragmented or multiple saccades occuring on only a small percentage of trials (27). And there is evidence suggesting that performance will suffer if the image is not stabilized (3) or if corrective saccades are required during stimulus exposure (16). In a set of trials with brief stimulus exposure, normal subjects would be expected to perform at a higher level than patients displaying dysmetric and/or low velocity saccades. The gaze of normals would arrive at the required location sooner, stabilize and have longer to take in information while that of patients would never or only very briefly acquire the target.

For large target displacements normal subjects shift gaze rapidly by combining a high velocity saccade with a lower velocity, longer duration, head movement; after the required shift, gaze is stabilized by the vestibulo-ocular reflex (VOR) generated compensatory eye movement during the remaining head movement. Clinical and experimental research using Method 2 of Table I demonstrates that patients with recent labyrinthine damage have great difficulty in such coordinated head and eye movement (10,28). These patients overshoot the target because of a lack of VOR generated compensatory eye movement or arrive later because of a "rounded" slower gaze shift. Patients with unilateral labyrinthine damage show a directional difference and take about one month to recover adequate coordination. Those with bilateral damage show overshooting and "rounding" in both directions and take up to 9 months to recover (28). Bilateral recovery appears to be due to an increase in cervico-ocular reflex gain and the pre-programming of compensatory eye movements (10). Patients with certain CNS disorders show saccadic dysmetria with and without head movement, though the frequency of dysmetria decreases with head movement (25).

Again normal subjects would be expected to perform at a higher level than patients demonstrating unstable gaze, late arrival, and corrective or dysmetric saccades during coordinated head and eye movement. The gaze of normal subjects would acquire the target more quickly and hold it for information intake, while that of certain CNS and vestibular patients would never or only briefly acquire the target.

The previous discussion has emphasized that time is a key factor in a potential performance-based test of oculomotor control. A key requirement in the development of a test sensitive to the described CNS and labyrinthine deficits is the establishment of an empirical relationship between performance on the test and the amount of time during which gaze is fixed on the target. Implied in this requirement is the ability to present targets for brief, precisely controlled intervals. A second major requirement is to insure that the requested gaze shift is actually produced by the subject.

An initial version of a test designed to meet the two important requirements above is described in the present report. Briefly it consists of a series of fixation letters presented at one location followed by a digit array presented at another. The subject reads aloud the letters, then as many of the digits as possible.

Three experiments were performed following test development. In one the fixation letters and digit array were presented at the same location; in the second, the digit array was displaced enough to require only eye movement; in the third, acquisition of the displaced array required coordinated head and eye movement. In all three the array inter-digit spacing and its exposure time were varied.

GENERAL PROCEDURE

APPARATUS

A Hewlett-Packard 9826 desktop computer was used to generate, store, retrieve and control the presentation of the stimuli in the present study. The onboard clock allowed timing of events to within 1/100th of a second. The visual stimuli were presented using one or two high-speed, vector graphics display systems. Both displays resolved 1020 x 1020 points, were equipped with grey glare shields and used P31 phosphor. The digit array was always presented on an HP 1321B X-Y display (21 inches diagonal) and the fixation letters were presented on the same display or on an HP 1317B X-Y display (17 inches diagonal). The displays were driven by independent HP 1351A Graphics Generators.

METHOD

Trial and Scoring Description

A single trial consisted of the same events throughout the study. These events are illustrated and described in Figure 1. From two to four fixation letters were presented for 0.2 seconds each with 0.2 seconds of blank display between the removal of one and the presentation of the next. A 1000 Hz tone of 0.2 seconds duration and the digit array were presented simultaneously 0.2 seconds after the removal of the last fixation letter. The tone was used to inform the subject that the array had been presented and became important only when the array was located in the periphery; it prevented the effect of digit array offset from being due to the difference in time taken to detect a central vs. peripheral visual event, that is, to a difference in detection-reaction time.

After a variable interval of 0.2 to 1.1 seconds the digit array was removed and a visual mask was presented at the same location. The mask allowed precisely controlled exposure times because it removed visual persistence of the digit array. The full horizontal and vertical extent of the array was covered by the mask. It was made up of the number of horizontal vectors equal to the number of vertical display points making up a digit (24 points). After 0.5 seconds the display was blanked until the next trial a few seconds later.

The subjects' task was to read the fixation letters aloud as they appeared, then to read as much of the digit array as possible from left to right. They were instructed to keep errors to a minimum but to try to read as many digits as possible. They were instructed to read them one at a time, not to group them (e.g., 3, 5, 9, not 359). The experimenter scored the trials from a tape recording of the session or during the session itself. For a trial to be counted, all the fixation letters had to be read in correct order. This insured relatively continuous gaze on the desired line of sight prior to shifting position to the digit array. The number correct was the dependent variable and it was defined as the number of digits read in correct order before any insertion, omission or transposition error.

TRIAL DESCRIPTION		
Time	Visual Stimuli	Comment
start	A R	Several randomly selected fixation letters were presented for short intervals. The subject was required to read each letter aloud as it was presented.
	8436247945	A stimulus array, consisting of 10 randomly selected, horizontally arranged digits was presented for an interval of variable duration. The subject read from left to right as many of the digits as possible. The performance measure was the number read in correct sequence.
finish		Following the digit array a visual mask was presented to insure precise exposure time and eliminate visual persistence.

Figure 1

Trial structure description for the test procedure used in the present study.

Stimuli Generation

The standard 1351A Graphics Generator alphanumeric characters were used as stimuli. Each character used in the study occupied 16 (horizontal) by 24 points on the display. The stroke width of the character was 1 point, giving a stroke width to character height ratio of 1/24. This is smaller than the recommended ratio of 1/7 to 1/10 for white characters on a dark background. However, given the luminance of the characters (below) this small ratio resulted in a more readable character than the recommended ratio. Each character subtended a visual angle of 14.2 minutes (horizontal) by 21.1 minutes. This character size falls within the recommended range of MIL-STD-1472B (17) for critical data with fixed position and luminance above 1 fL. A Photo Research Corporation Pritchard Photometer was used to measure a 20 minute circular field; the average luminance of a character was 2 fL (6.85 cd/m^2). With inter-digit spacings of 3.5, 7.1 and 14.2 minutes the luminances within a 1 degree circular field were 3, 2.6 and 2.2 fL* respectively. The visual mask had a luminance of 10.8 fL within the same field.

All of the capital letters were available for use as fixation letters with the exception of Q, O and W. Q was eliminated because of its high similarity to O for the characters used. W was eliminated because it is a two syllable character; and O was eliminated because of its confusability with zero.

Two, three or four fixation letters were presented on a single trial. The number presented on any given trial was randomly determined with the constraint that each number was presented an equal number of times with each condition. This control prevented a confounding of the effect of the independent variables with any systematic effect due to the number of fixation letters. The particular letters presented were chosen at random from the remaining 23 (see above), subject to the constraint that the same letter could not be presented twice in sequence.

The digits chosen for the stimulus array consisted of the numbers 2-9. The number 1 was excluded because it did not span a horizontal angle equal to the remaining characters, zero because of its confusability with the letter O. The digits which filled the 10 character array were selected at random from the remaining eight subject to the following constraints: (1) the same digit could not appear twice in sequence; (2) no three digit runs were allowed in which the values of the three were one or two greater or less (e.g., 2,4,6 or 9,8,7). The first constraint eliminated scoring problems possible with unclear enunciation, the second prevented the use of simple memory aids from influencing the number of digits correctly read from the display.

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*To obtain number of cd/m^2 multiply the number of fL by 3.426.

EXPERIMENT 1

The purpose of this experiment was to provide a letter-digit reading performance baseline under conditions requiring no head or eye movement to acquire the digit array. The most important consideration was that of the functional relationship between performance and array exposure time. Without a well defined, orderly relationship the potential usefulness of the test would be markedly diminished. "Ceiling" and "floor" effects were avoided by setting values for exposure time after several preliminary subjects.

Of secondary importance was the effect of inter-digit spacing on performance. Recent work by Barnes, Turnipseed and Guedry (4) has shown that wider spacing between characters leads to improved performance during vestibular nystagmus. They suggested that this may be due to a decrease in overlap of blurred images in the visual system. Although nystagmus was not a consideration in the present study, it might be expected that a decrease in visual blurring with wider character spacing should improve performance following target acquisition with high velocity head and eye movements. Of course the present experiment involved no such movements; the digit spacings used here served only as a baseline for later experiments.

PROCEDURE

Subjects

The subjects were 19 Naval and Marine flight candidates who ranged in age from 20-25 years. All had recently passed the flight physical. One additional subject was a 43 year old technician, also in good health.

Method

A total of 12 conditions were formed by combining four exposure times (0.2, 0.5, 0.8, 1.1 seconds) with three inter-digit spacings (3.5', 7.1', 14.2' visual angle). The largest spacing was equal to the width of a character and the smallest equal to 1/4 the character width. The smallest spacing exceeds the minimum established by MIL-STD-1472B (17). With character spacings of 3.5, 7.1 and 14.2 minutes visual angle, the entire 10 digit array subtended $2^{o}52'$, $3^{o}23'$ and $4^{o}31'$ respectively. Table II contains this information along with the display points used by a single character and the full 10 character array.

The subject was seated 112 cm from and directly in front of the display. The bottom left corner of the leftmost digit in the array served as a reference point. The subject moved the point so that it was at a comfortable vertical eye level. Horizontally both it and the subject's head position were in the middle of the display.

The subject was then given 48 practice trials without fixation letters to produce proficiency in digit reading before addition of the task involving fixation letters. There were four blocks of 12 trials, with each condition appearing once in each block. The order of presentation of conditions within blocks was randomized.

TABLE II

Spacing Characteristics for Experiments 1, 2, 3

Space Between Digits[a]	Display Points Between Digits[b]	Total Space of Array	Total Display Points of Array
3.5'	4	$2^{O}52'$	196
7.1'	8	$3^{O}23'$	232
14.2'	16	$4^{O}31'$	304

[a] Space occupied by one digit was 14.2' (horizontal) by 21.1'.

[b] Points occupied by one digit were 16 (horizontal) by 24.

During the test trials a sequence of two, three or four fixation letters was presented at the same display location (e.g., bottom left corner at reference point) as the leftmost digit in the array. The subject was instructed to read each letter aloud as it appeared, and then to begin reading the digit array immediately after presentation. A total of 72 trials were presented to each subject with a short break at the halfway point. Each number of fixation letters (two, three or four) was paired with each condition twice, once before and once after the break. The 72 trials were broken into six blocks of 12 with each condition occurring once in each block. The order of presentation of conditions within blocks was randomized.

RESULTS AND DISCUSSION

There are three components to the analysis of data in the present experiment: 1) an analysis of variance which examines the influence of inter-digit spacing and digit array exposure time on performance; 2) a linear regression analysis of the functional relationship between performance and exposure time; 3) an examination of systematic change occurring over trials.

Analysis of Variance

To analyze variation due to spacing and exposure time the data over the replications of each condition were collapsed to produce a mean for each subject in each of the 12 conditions. Replications were not included as a factor for the following reasons. 1) The six trials were identical only in the levels of exposure time and spacing, not in the letter-digit stimuli. One might still consider these as replications except that in conducting the experiment it became clear that individual subjects had trouble with some combinations, causing variation in performance. This is connected to the second reason. 2) Several trials were eliminated because subjects failed to correctly read the fixation letters (13 trials out of a total 1440 or 0.9%; no more than one trial in any condition for any subject). 3) The six trials in each condition were given only to provide a stable performance measure for each subject. If replications were of interest more trials would have been included. For these reasons the data were collapsed over the five (1 missing point) or six replications and entered into a treatment x treatment x subjects (8) or repeated measurements (20,31) analysis of variance.

There is a significant increase in number of digits correct with exposure time, $F\ (3,57) = 637$, $p < .001$. Though exposure time had a profound effect on performance, inter-digit spacing did not. Neither its main effect ($F < 1$) nor its interaction with exposure time ($p > .25$) even approached significance. The means and standard deviations are nearly identical for the three levels of spacing used here under static conditions.

Linear Regression

The mean number correct (± 1 SD) are plotted in Figure 2 as a function of exposure time. The relationship appears positive and linear. This is supported by a multiple linear regression analysis. Because the data are from a full factorial design with an equal number of data points in each cell, the effects of spacing and exposure time are mutually orthogonal and may be considered independently (11,20). The linear regression equation accounted for a significant portion of the total variance, $F(2, 237) = 718$, $p < .001$. The multiple correlation is .926 and the equation accounted for 86% of the total variation. As might be expected from the analysis of variance, spacing contributed nothing to the equation under conditions of static head and eyes ($r = -.001$). Exposure time exerts a positive, linear effect on performance ($r = .927$) with an increase of 3.73 correct digits for each second of exposure. The equation is

$$C = 3.73 \times (T) + 2.13,$$

where C is the number correct, T is exposure time in seconds and 2.13 is a constant.

The values obtained are not as important as the existence and nature of the relationship between exposure time and performance. Without a strong, systematic relationship the entire approach would have to have been reconsidered. As it currently stands, though in later experiments it can be assumed that once gaze acquires the digit array and stabilizes, there will be a linear increase in number correct with an increase in exposure time. The equation above will be used to predict performance in those experiments using estimates of gaze arrival delay.

Learning, Practice or Fatigue Over Trials

The six trials in each condition were divided into those that occurred in the first half and the second half of the session (see procedure). A simple mean was calculated over the two (one missing point) or three trials in each half for each subject. Collapsed over spacing and exposure time 12 of the 20 subjects showed a slight improvement, 7 showed a decrement and one showed no change. The correlation between the first and second halves is .77, $p < .001$. A non-directional t-test revealed only a marginal improvement over trials, $t(19) = 1.84$, $.10 > p > .05$.

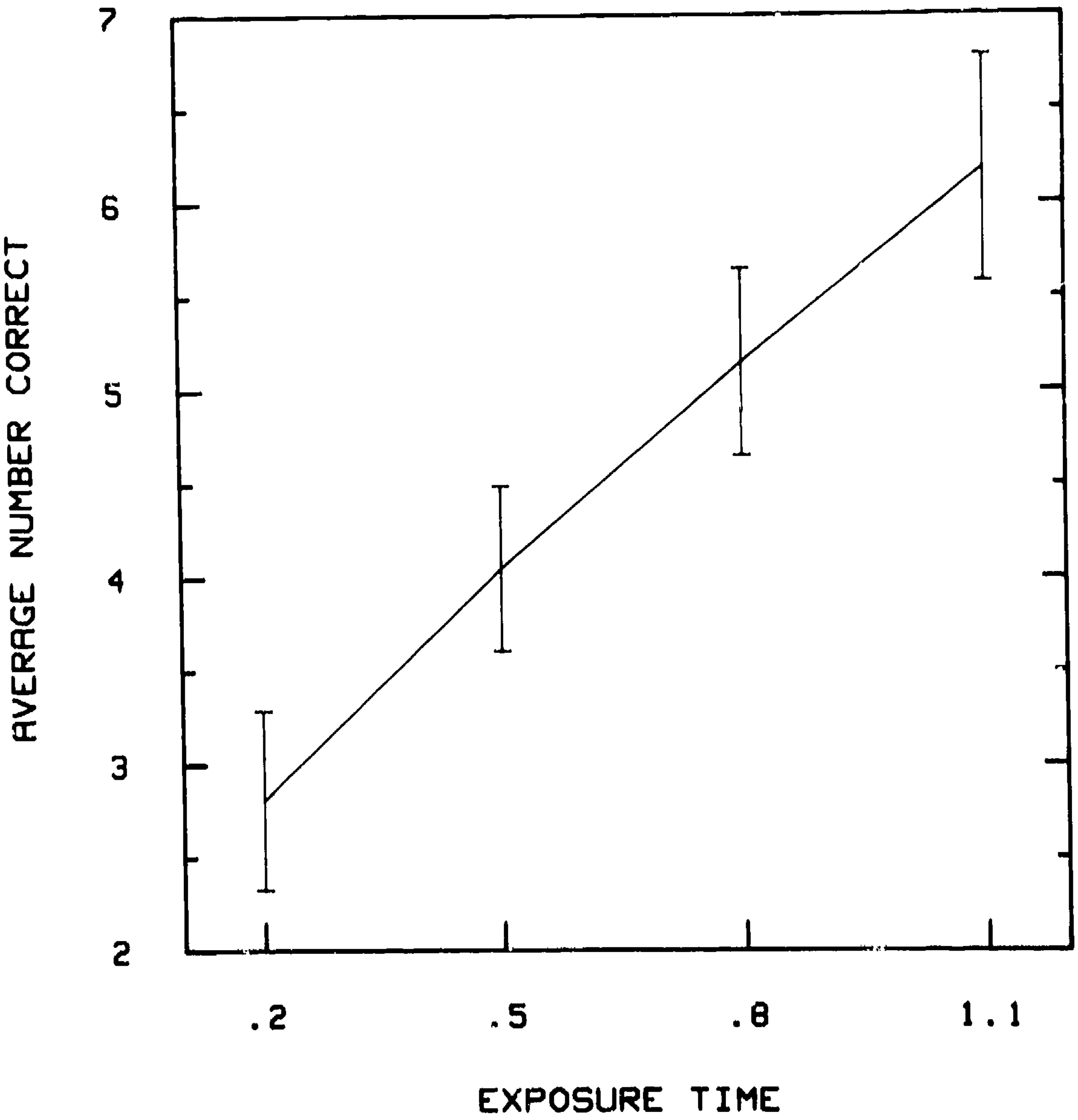

Figure 2

Mean Number Correct Responses (± 1 SD) as a Function of Exposure Time, Experiment 1

Although improvement is statistically marginal there is at least a suggestion that subjects are improving over trials. One possibility is that they are gaining experience over trials with the combined letter-digit reading task. In the later experiments practice on the complete task was given prior to the test trials. Under these conditions the suggestion of improvement over test trials disappeared.

SUMMARY

Under conditions not requiring head or eye movement to acquire the stimulus array there exists the necessary, strong functional relationship between exposure time and performance. The inter-digit spacings were greater than the minimum required under MIL-STD-1472B. As might be expected there is no effect of spacing above that minimum under static conditions.

EXPERIMENT 2

The purpose of this experiment was to examine performance on the potential test when eye but not head movement was required to acquire the digit array. The fixation letters were presented at a single, central display location; the digit array was presented at that central location or displaced horizontally by $\pm$ 2.5° or $\pm$ 5°. The effects of displacement on performance along with that of inter-digit spacing and exposure time were examined in the present experiment.

Target displacement (or offset) and exposure time are inter-related in their effect on performance because both influence the duration of the interval that the subject is able to fixate the digit array. Exposure time is the total time the digit array is presented on the display. The fixation interval is the exposure time minus any time taken to acquire the digit array.

In Experiment 1 the fixation interval was assumed to be equal to exposure time because the digit array was acquired without the necessity of eye movement. In the present experiment the fixation interval is somewhat smaller than exposure time for the digit array positions displaced from the fixation letters. An estimate of the difference has been provided by previous research (9) on saccade characteristics. Generally, saccadic reaction time is estimated to be about 200 msec*. In addition to reaction time, there is a short time taken to complete a saccade once it is initiated. For a saccade of about 5°, this time is about 30 msec. The difference between exposure time and fixation time for the 5° offset would be expected to be about 230 msec; for an offset less than 5° the difference would be slightly less than that. Because of the relationship between exposure time - fixation time and performance in Experiment 1, one would expect a decrease in fixation time to produce a lower level of performance. At a minimum there should be a difference between the position not requiring movement (zero offset) and those requiring movement ($\pm$ 2.5° and $\pm$ 5°). Whether the test is sensitive enough to pick up the slightly longer fixation time for the 2.5° offset was not clear *a priori*.**

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*This may be increased substantially if the subject is performing a central continuous task before the required head and eye movement (21).

**For displacements of less than 5°, saccades tend to be of constant duration rather than constant velocity, thus differences between 2.5° and 5° displacements are not necessarily to be expected.

As mentioned in Experiment 1, previous research on inter-digit spacing has shown that wider spacing produces better performance during vestibular nystagmus (4). Under the static conditions of Experiment 1 there was no advantage for wider inter-digit spacing; under the static condition in the present experiment (zero offset) a similar lack of advantage is expected. It has long been known that an increase in visual thresholds for detection, resolution and recognition are associated with the occurrence of voluntary saccades (9). The suppression of vision begins 50-100 msec before, reaches a peak during, and lasts until 50-100 msec after the saccade. A study using very fast exposure times, where retinal smear is minimal, has found visual suppression, thus implicating a central inhibition of vision (29). In another study horizontal stripes were more easily resolved than vertical ones during horizontal saccades, though both were increased substantially over static thresholds (18). The authors estimate that approximately 80% of the visual suppression during a saccade is of central origin, while the remainder is due to a smearing of the image on the retina. In the eye movement conditions of the present experiment one might expect that the horizontal digit array would contribute some small amount of smearing as the eye moved into position for reading. This smearing would seem to be greater for narrow character spacing, because of a higher luminance within a unit display area, and for movement to the left, because most or all of the array must be passed over by the eye as it moved into position for reading.* Therefore, performance might be expected to decrease slightly in these conditions.

PROCEDURE

Subjects

The subjects were 12 Naval and Marine flight candidates who ranged in age from 20 - 25 years. All had recently passed the flight physical. None had participated in Experiment 1.

Method

A total of 20 conditions were formed by combining two exposure times (0.5, 1.1 sec) with two inter-digit spacings (3.5', 14.2' visual angle) and five array offsets from fixation (0°, $\pm 2.5^{\circ}$, $\pm 5^{\circ}$). Figure 3 presents a simulation of the offset and spacing used in this experiment. Note how in this figure the offset has been defined to be the space between the fixation letter's lower left corner and the same corner for the leftmost digit in the array. This was done because the digits were read from left to right. Table III presents information on the visual angles and display points for these conditions of offset and spacing.

As in Experiment 1 the subject was seated 112 cm from the display. The reference point was adjusted to a comfortable vertical eye level. Horizontally both it and the subjects position were slightly left of display center (see Figure 3). The instructions and initial 48 practice trials were the same as those described in Experiment 1.

After completion of these trials it was explained that the position of the fixation letters would remain the same throughout but that of the digit array would randomly vary from trial to trial. They were asked not to guess its location ahead of time but rather to respond after presentation. Following

*Saccadic suppression is minimal with supra-threshold visual stimuli (Riggs, et al., Vision Res. 22 991-996, 1982); thus smear may be a factor.

Table III

Spacing and Offset Characteristics from Experiment 2

DISPLAY POINTS			VISUAL ANGLE FROM FIXATION POINT	
Array Beginning[a]	Points Between Characters[b]	Ending Point[c]	First Character[e]	Last Character[f]
16	4	212	$-4^{\circ}58'$	$-2^{\circ}6'$
	16	320	$-4^{\circ}58'$	$-34'$
187	4	383	$-2^{c}31'$	$9'$
	16	491	$-2^{\circ}31'$	$1^{\circ}54'$
358[d]	4	554	0	$2^{\circ}52'$
	16	662	0	$4^{\circ}31'$
529	4	725	$2^{\circ}31'$	$5^{\circ}20'$
	16	833	$2^{\circ}31'$	$7^{\circ}1'$
700	4	896	$4^{\circ}58'$	$7^{\circ}50'$
	16	1004	$4^{\circ}58'$	$9^{\circ}24'$

[a] Display was 1020 x 1020 points.
[b] Characters occupied 16 points.
[c] Display widths were 196 and 304 points for 4 and 16 points spacing respectively.
[d] Location of fixation point.
[e] Reference lower left corner.
[f] Reference lower right corner.

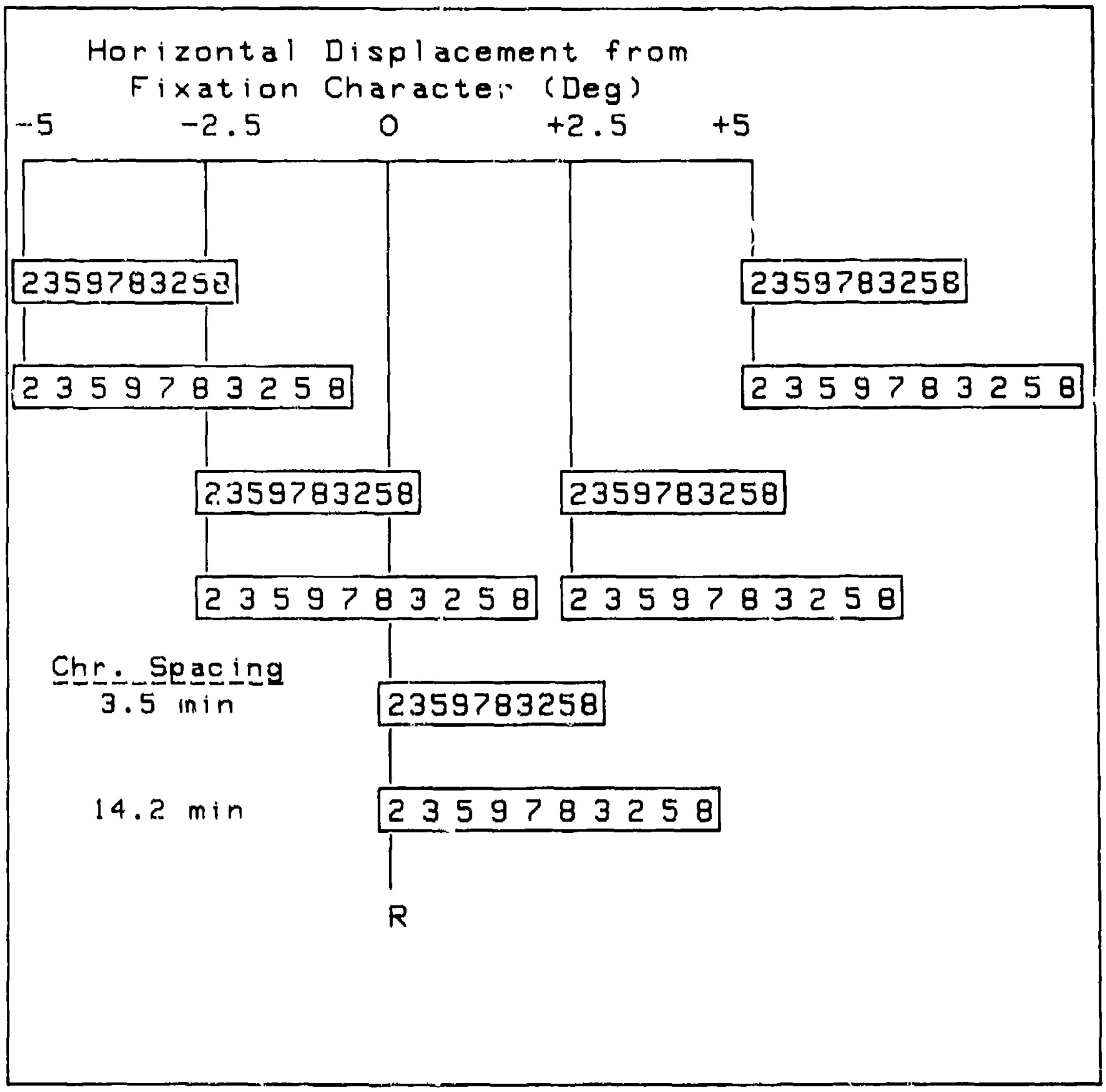

Figure 3

Simulated visual conditions of spacing and offset, Experiment 2. The letter "R" appears at the horizontal position where the fixation letters were presented. There was no vertical displacement; i.e., the digits appeared to the right or to the left of the fixation letters.

these instructions each subject was given 20 practice trials. Each of the 20 conditions (2 exposure times x 2 spacings x 5 positions) was presented once in a random order.

After practice, 120 test trials were presented with a short break at the halfway point. Each number of fixation letters (two, three or four) was paired with each condition twice, once before and once after the break. The 120 trials were broken into six blocks of 20, with each condition occurring once in each block. The order of presentation of conditions within blocks was randomized.

RESULTS AND DISCUSSION

There are three components to the analysis of data in the present experiment: 1) an analysis of variance with a set of a posteriori comparisons examining the effects of exposure time, spacing and offset on performance; 2) a multiple linear regression analysis of the functional relationship between performance and those three variables; 3) an examination of systematic change occurring over trials.

Analysis of Variance

For this analysis the data over condition replications were collapsed to produce a mean for each subject in each of the 20 conditions. Replications were not included as a factor for the same reasons as those described in Experiment 1. There are 23, or 1.6%, missing data points out of a total of 1440; no more than one point is missing for any subject in any condition. The mean for each subject in each condition then was taken over five or six trials and entered into a three-way repeated measures (20,31) or treatment x treatment x treatment x subjects (8) analysis of variance.

There is a significant increase in number of digits correct with wider inter-digit spacing, $F(1,11) = 13.04$, $p < .005$, and with exposure time, $F(1,11) = 931.42$, $p < .001$ and significant decrease with increasing offset $F(4,44) = 15.92$, $p < .001$. There is also a significant interaction between offset and spacing, $F(4,44) = 2.95$, $p < .05$. No other interactions are significant.

Looking first at exposure time, the difference between the number correct for 0.5 and 1.1 seconds is quite similar in Experiments 1 and 2 (about 2 digits). Of course the overall values here are lower than those obtained in Experiment 1 because of a decrease in time available for fixation by an amount equal to saccade reaction time and duration. If that delay is estimated the regression equation from Experiment 1 can be used to predict performance as a function of time. In the case of zero offset, exposure time is used; for $\pm 5^{\circ}$ the value for time is reduced by 0.23 seconds (9). Table IV presents the values predicted in this way along with those actually obtained. Despite the differences between the experiments and the rough estimates of reaction time and saccade duration, the predicted and obtained values fall reasonably close to each other.

The obtained values fall closer together than predicted suggesting a lower slope than that obtained in Experiment 1. A difference in intercept would be expected if the gaze arrival delay were high or low, but the difference in slope suggests that rate of increase in number correct as a function of time was less than that in Experiment 1. One difference in procedure for the two experiments* was that the digit array position was always the same in Experiment 1 while it varied randomly

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*Considering Ns used, sample differences could also account for slope differences.

among five positions in Experiment 2. This may have affected slope somehow, but one would expect that it would affect gaze arrival delay, and thus the intercept, because of an effect of uncertainty upon saccade reaction time.

TABLE IV

Predicted and Obtained Number Correct for Zero and $\pm 5^{\circ}$ Degree Offsets, Experiment 2

Exposure Time	Stimulus Offset	Predicted Correct[a]	Obtained Correct[b]
0.5	$\pm 5^{\circ}$	3.13	3.32
	0	3.98	3.74
1.1	± 5	5.37	5.21
	0	6.23	5.88

[a] Using linear regression equation from Experiment 1.
$C=2.125 + 3.729 \times (T)$,
Where C is number correct and T is exposure time in seconds. For $\pm 5^{\circ}$ T was reduced by an estimated RT and saccade duration of 0.23 sec.

[b] Means for data collapsed over spacing and $\pm$ offsets.

Although both offset and spacing produce significant variation, their interaction complicates the interpretation somewhat. The interaction was analysed a posteriori with the Neuman-Keuls studentized range statistic (31, pp. 185-201 and 240-273). All possible treatments were compared at $p < .05$ level. The comparisons of interest are 1) the effect of spacing at each offset, 2) the difference due to spacing, and 3) the directional difference for offset.

As may be seen in Figure 4, there is no effect of spacing when eye movement is not required (zero offset). At offsets away from zero there is a tendency toward better performance for the more widely spaced array. The range statistic revealed a reliable advantage at the -5° and 2.5° offsets only. Although the effect of spacing is small in magnitude and less reliable than might be hoped it is nevertheless in the direction that would be expected from the work of Barnes, et al. on spacing (4) and related work on the suppression of vision during saccadic eye movement (16,18,19,29,30).

With respect to offset, performance generally declines away from zero in either direction. This is what would be expected given the reduction in time available for fixation when eye movement is required. The range statistic reveals a reliable decrease in performance at all

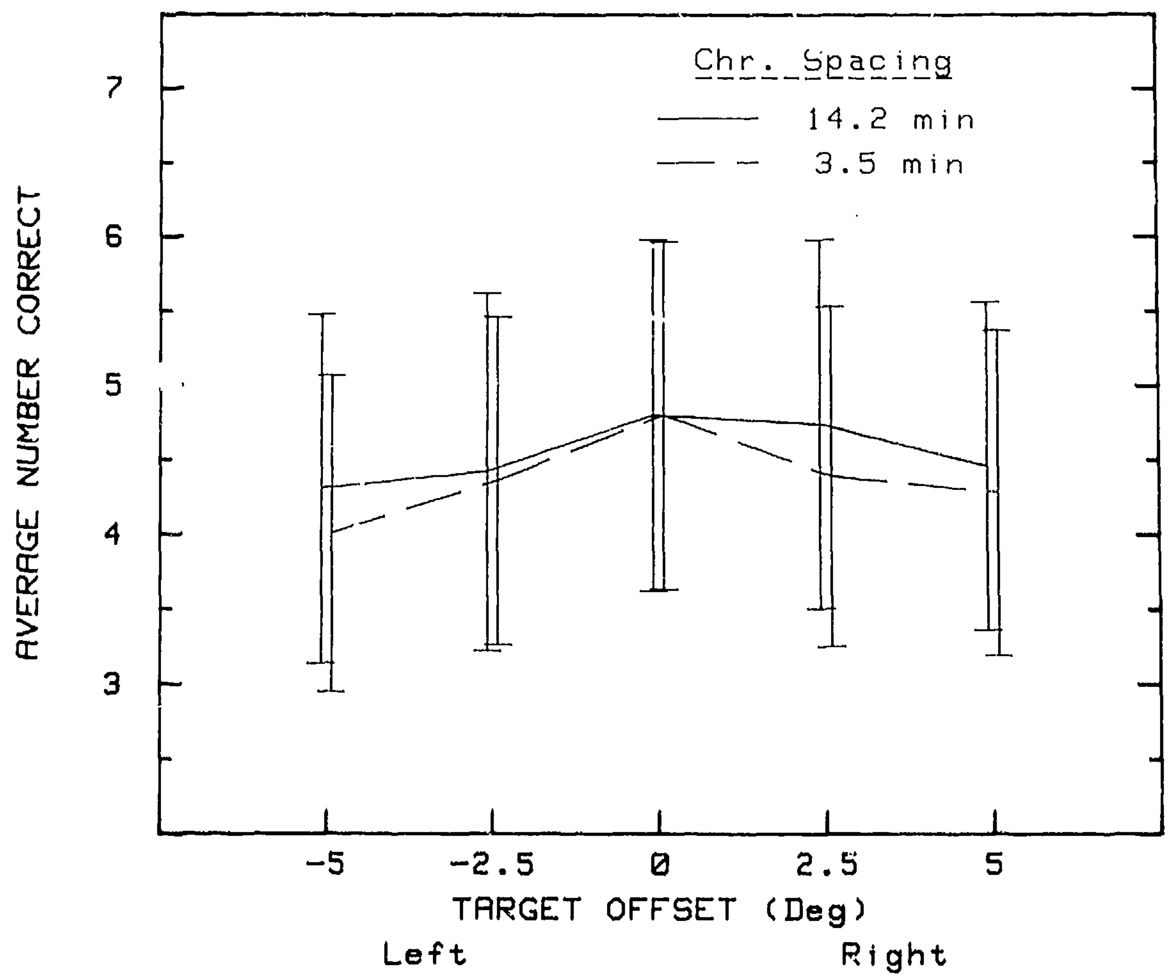

Figure 4

Interaction between offset and spacing, Experiment 2. Shown are average number correct digits ± 1 SD.

offsets away from zero except 2.5° for wide spacing. Possible reasons for this negative effect are not clear at this time.

Concerning the potential test's sensitivity to very small differences in fixation time the results are somewhat mixed. In the introduction to this experiment the small expected difference in delay of arrival for 2.5° vs. 5° (to the same side) was discussed. In Figure 4 there is a suggestion of lower performance and thus later arrival for both directions of movement. However, the difference between 2.5° and 5° is reliable only for leftward movement for narrow spacing and rightward movement for wide spacing. In general the potential test will probably not be suitable for detecting this small difference.

A directional difference would be revealed by a difference in performance for right vs. left eye movement. In general performance is better for conditions requiring movement to the right than to the left. These differences are reliable at 2.5° for the wide spacing and 5° for the narrow spacing. There are several possible reasons for the advantage of eye movement to the right. One is that saccades are more accurate in that direction and, as a result, the target is acquired faster. Two recent papers have in fact reported that small rightward eye movements require fewer corrective saccades (2) or are more accurate (12), though the amplitudes of eye movement where this occurred were larger than in the present experiment. Another possible reason is that in leftward movement there is a small amount of smearing of the digit array caused by a requirement for the eye to pass over the digit array during the saccade. This is illustrated in Figure 3 which shows the eye had to pass over the array to reach the leftmost digit for leftward, but not rightward eye movement. As the short review of the suppression of vision during a saccade in the introduction to this experiment suggests, one would expect the contribution of smearing to poor performance to be small. A third possibility is that there is some difference in the efficiency with which the eyes can change direction after stopping as opposed to continuing in the same direction. One might suppose that continuing in the same direction, as required by rightward eye movement, might be more efficient than a change of direction, as required by leftward movement. There seems to be little evidence on this particular question. At the present time it is probably best to suggest that saccades of greater accuracy to the right produce better performance in that direction, while smearing may slightly depress performance for movement to the left. Further research is needed into this area because it may have an impact on later test development.

Multiple Linear Regression

Because of the suggestion of a directional difference in eye movement and because a later experiment considered only rightward movement, a multiple regression equation was developed for the data from 0°, 2.5°, 5° offsets (zero or rightward movement) at both exposure times and spacings. Like Experiment 1, the data are from a factorial design with an equal number of points in each condition. As a result the three variables are mutually orthogonal and their effects may be considered independently (11,20).

The multiple regression equation accounted for a significant portion of the total variance, $\underline{F}$ (3,140) = 306, $\underline{p} < .001$. The multiple correlation is .931 and the proportion of variance accounted for by the equation is 87%. As suggested by the analysis of variance there is a strong positive relationship between exposure time and performance ($\underline{r}$ = .915) which accounts for about 84% of the systematic variance. There is a small negative effect of increasing offset ($\underline{r}$ = -.154) which accounts for about 2% of the variance. Inter-digit spacing exerts a very small positive influence ($\underline{r}$ = .077) and accounts for less than 1% of the systematic variation. The equation is

$$C = 1.85 + .01 \times (S) + 3.5 \times (T) - .09 \times (F),$$

where C is number correct, S is spacing, T is exposure time in seconds, F is offset in degrees and 1.85 is a constant.

Again the values obtained are not as important as the presence of a functional relationship between these variables and performance. All act in the expected direction and together they account for a large, significant portion of the total variance.

Learning, Practice or Fatigue Over Trials

As in Experiment 1 the six trials in each condition were divided into those that occurred before and those that occurred after the halfway point. A simple mean was calculated over the two (one missing data point) or three trials in each half. Collapsed over spacing, offset and exposure time, 3 of the 12 subjects showed a slight improvement, 5 showed a decrement and 4 showed no change. The correlation between the first and second halves is .80, $\underline{p} < .001$, a value very close to that obtained in Experiment 1. A non-directional $\underline{t}$-test showed no significant difference between the two halves, $\underline{t}(11) = 0.59$, NS.

After the results of Experiment 1 suggested a possible practice effect, additional practice trials were added in Experiment 2. These trials, involving combined letter-digit reading under the actual conditions of spacing, offset and exposure time, seem to have brought performance to a relatively stable level.

SUMMARY

Under conditions requiring eye but not head movement, performance on the potential test is again quite orderly and predictable. Generally, spacing, exposure time and offset influence performance in the expected direction. Performance consistently increases with exposure time, generally increases with spacing and decreases with offset. Spacing has no effect when eye movement is not required (zero offset). A small directional difference favoring rightward movement might be due to more accurate saccades in that direction or some other factors. Although some differences in performance were detected between small eye movement amplitudes the test is probably not going to be consistently sensitive to them. Performance is relatively stable over trials.

EXPERIMENT 3

The purpose of this experiment was to examine performance on the potential test when coordinated head and eye movement were required to acquire the digit array. The fixation letters were presented at the center of one display and the digit array was presented at the center of a second display, displaced by 45° or 85° from fixation. The effect of displacement (offset) along with that of inter-digit spacing and exposure time were examined here.

As described in Experiment 2 target displacement and exposure time are inter-related in their effect on performance. Both influence the residual fixation interval for the digit array. In Experiment 1 the fixation interval was assumed to be equal to exposure time because the digit array was acquired without eye movement. In the eye movement conditions of Experiment 2 the fixation interval was estimated to be exposure time minus a 0.23 seconds period for saccade reaction time plus travel time. In that experiment predicted performance closely matched that actually obtained. In the present experiment the delay in arrival at the digit array includes gaze (sum of head and eye position) reaction time and travel time. The components involved here include head and eye reaction time and saccade and head movement velocity. After the saccade is completed, gaze is stabilized by counterrotation of the eyes at a rate proportional to that of the head. Estimates for the delay in gaze arrival at the target as a function of offset have been provided by human engineering research (23). The estimated delays are 0.242 and 0.382 seconds for the 45° and 85° offsets used in the present experiment. If gaze is effectively stabilized following completion of the saccade one would expect test performance to be a linear function of the time remaining for fixation.

Under conditions requiring eye movement the results of Experiment 2 suggest slightly better performance with the more widely spaced array. The conditions of movement in the present experiment are slightly more complicated because of the requirement for coordination of head and eyes. Among these normal subjects the shift in gaze essentially ends with the saccade. As in Experiment 2 a slight advantage for the more widely spaced array is expected here. Of course, an even larger advantage would be expected if the subject was not able to stabilize with appropriate counterrotation. This situation would be more like that of the involuntary nystagmus investigated by Barnes, et al. (4).

PROCEDURE

Subjects

The subjects were 16 Naval and Marine flight candidates who ranged in age from 20 - 25 years. All had recently passed the flight physical. None had participated in Experiments 1 or 2.

Method

A total of 12 conditions were formed by combining three exposure times (0.5, 0.8, 1.1 seconds) with two inter-digit spacings (3.5', 14.2' visual angle) and two digit array offsets from fixation (45°, 85°). Figure 5 presents a diagram of the offsets used here. Two items should be noted. One is that the position of the stimulus display relative to the subject did not change; it remained at 45°. For the offset of 45°, the fixation display was at zero,

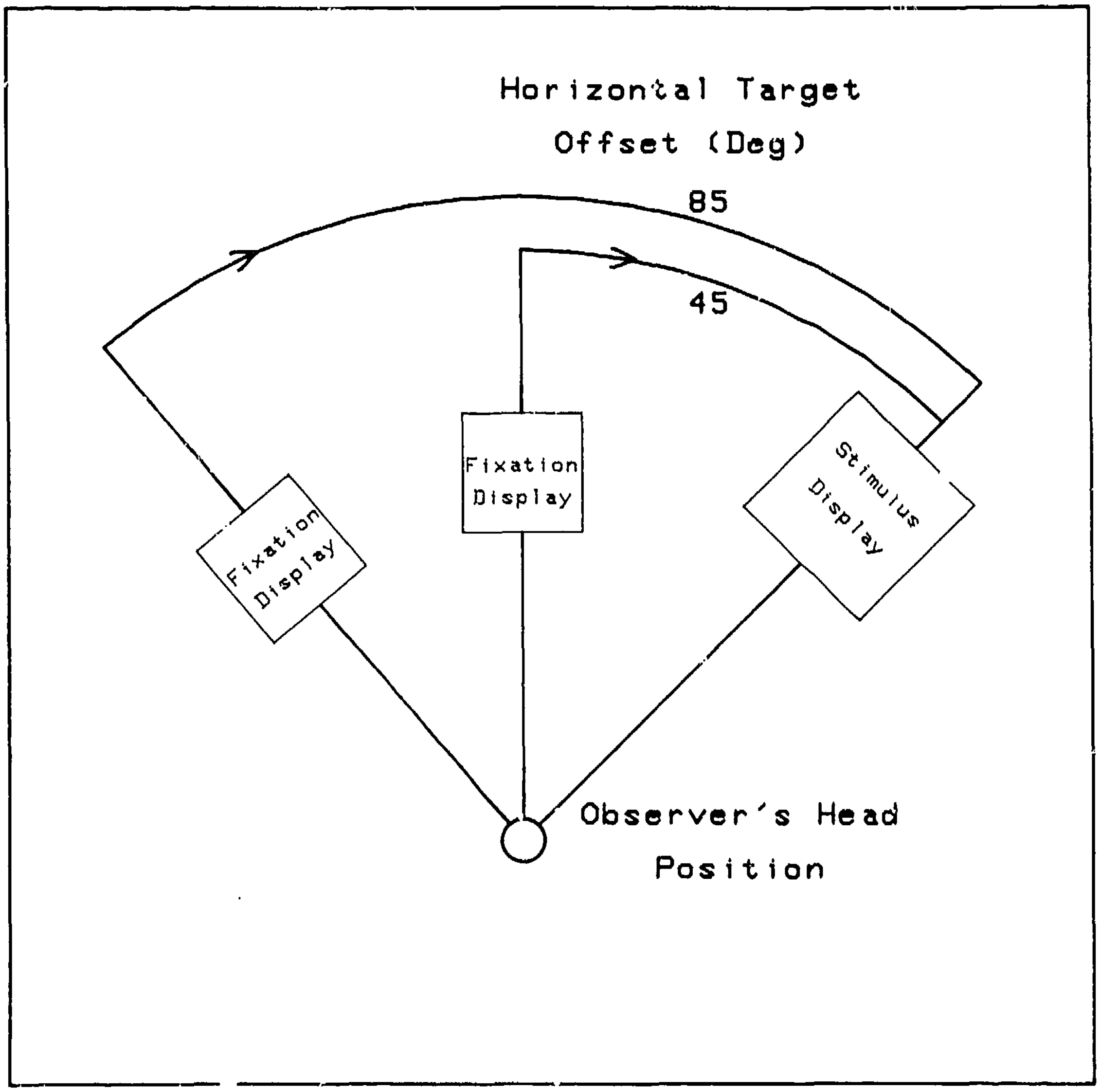

Figure 5

Layout of Offset Conditions, Experiment 3.

for 85° at -40°. A second point is that the fixation display was closer to the subject than the stimulus display (89 and 112 cm respectively). This was necessary to keep the visual angle subtended by the fixation letters on the smaller display equal to that of the digits; this kept the letter-digit size relationship equal in all three experiments.*

The reference point was horizontally in the center of each display. The subject adjusted the vertical level to a comfortable reading height. The instructions and 48 practice trials were the same as those described in Experiment 1. The initial practice trials were presented on the stimulus display.

After completion of these trials the subject received instruction on the combined letter-digit reading task. Several fixation letters were to appear on the display to the subject's left. He or she was to turn (the head) to face that display squarely while reading the letters aloud. When the auditory tone and digit array were presented the subject was to turn head and eyes to face the second display and read the digits as before. The final position of the head was to be square to that display. During the trials subjects were told whenever the start or finish positions were not approximately correct. Most subjects corrected starting position before the trial and finishing position on the next trial.

Horizontal head and eye position were measured with a system developed by Jell, Guedry, and Hixson (14). Briefly, electrooculography (EOG) was used for eye position and a lightweight head frame attached to a freely rotating potentiometer for head position. Both signals were recorded on paper and magnetic tape. EOG was calibrated before and after each offset condition. Head position was calibrated before and after the test trials.

The order of offset presentation was counterbalanced across subjects. At each offset there were 18 practice trials, three each of the six exposure time-spacing combinations in a random order. Following the practice trials there were 54 test trials, nine each of the six exposure time-spacing combinations in a random order. Each number of fixation letters (two, three or four) was paired three times with each condition, once in each block of 18 trials. During a short break the fixation display was moved to the other position. The subject then completed a set of 18 practice and 54 test trials at that offset

RESULTS AND DISCUSSION

There are four components to the analysis of data in the present experiment: 1) an analysis of variance with a set of a posteriori comparisons examining the effects of exposure time, spacing and offset on performance; 2) an analysis of performance predicted from the regression equation of Experiment 1 and estimates of gaze arrival delay; 3) a multiple linear regression analysis of the functional relationship between performance and spacing, offset and exposure time; 4) a brief description of the patterns of coordinated head and eye movement. Change over trials (replications) was not analyzed because of the negative findings in the two previous experiments.

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*Requirements for accomodation and vergence changes were the same for both the 45° and 85° movements because the distances from the eye to the fixation display (89 cm) and to the target display (112 cm) were the same for both angular displacements; however, comparison with Experiments 1 and 2, in which displays were at a constant 112 cm distance, could be affected.

Analysis of Variance

For this analysis the data over condition replications were collapsed to produce a mean for each subject in each of the 12 conditions. Replications were not included as a factor for the same reasons as those described in Experiment 1. There were 28 or 1.6% missing data points out of a total of 1728. No more than two out of nine trials is missing for any subject in any condition. The mean for each subject in each condition then was taken over seven to nine trials and entered into a three-way repeated measures analysis of variance.

There is a significant decrease in number correct with increasing offset, $F(1,15) = 50.8$, $p < .001$, and a significant increase with wider spacing, $F(1,15) = 24.3$, $p < .001$ and increasing exposure time, $F(2,30) = 302$, $p < .001$. Significant interactions exist between offset and exposure time, $F(2,30) = 18.3$, $p < .001$, and spacing and exposure time, $F(2,30) = 4.5$, $p < .05$. The three-way interaction is also significant, $F(2,30) = 8.4$, $p < .005$.

The interactions were analyzed by using the Neuman-Keuls studentized range statistic for comparing all possible treatments. The three-way interaction is presented in Figure 6. The effect of exposure time is consistent over offset and spacing. An increase in exposure time at any combination of offset and spacing is associated with a significant increase in performance. There is a significant decrease in performance for the larger offset and an increase in performance for the wider spacing with the condition means generally following these trends. However, the differences are not always reliable ($p < .05$). Spacing produces a reliable difference at 1.1 seconds exposure time and 45° offset, and at 0.5 sec exposure and 85° offset. Offset produces a reliable effect at the shortest exposure time for both spacings; its effect is also reliable at 0.8 seconds exposure and narrow spacing, and at 1.1 seconds exposure and wide spacing. There appears to be no consistent pattern among these effects. Although the test is sensitive to these variables, it is not as sensitive or consistent as might be hoped with respect to spacing and offset. These are the same conclusions drawn concerning these two variables in Experiment 2.

Predicted Performance

Assuming that the effect of offset is to reduce the amount of time available for fixation, performance can be predicted using the regression equation from Experiment 1 and the estimates of time reduction from Robinson, et. al. (23). The estimates were subtracted from exposure time to predict test performance. Table V presents the predicted and obtained levels of performance for the offsets used in the present experiment. One can see that the tabled values for predicted and obtained performance fall quite close to each other. This is quite important because it suggests that the test behaves in a systematic, predictable way. Given the empirical estimate for arrival delay with eye movement, the equation developed in Experiment 1 predicts performance in Experiment 2 quite well. Given the estimate for arrival delay with coordinated head and eye movement that equation closely predicts performance in Experiment 3. This is quite encouraging because Experiments 1, 2, and 3 involved different subjects; one would expect even better prediction if the equation were based on the performance of the same subjects.

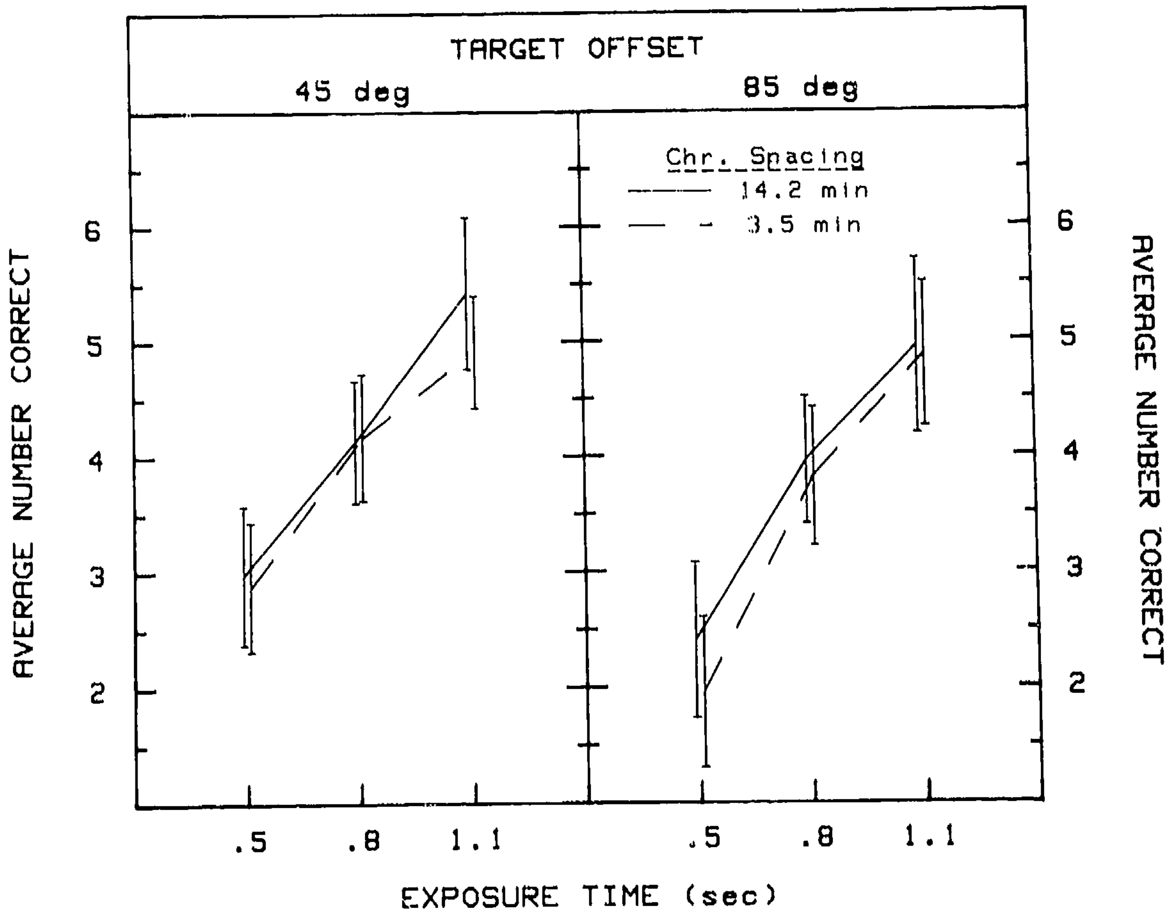

Figure 6

Interaction between offset, spacing and exposure time, Experiment 3. Shown are average number correct ± 1 SD.

TABLE V

Predicted and Obtained Number Correct Digits as a Function of Offset and Exposure Time, Experiment 3

Offset (Deg)	Exposure Time (Sec)	Predicted Correct[a]	Obtained Correct[b]
45	.5	3.08	2.93
	.8	4.21	4.15
	1.1	5.32	5.17
85	.5	2.57	2.19
	.8	3.68	3.89
	1.1	4.80	4.92

[a] Using linear regression equation from Experiment 1.

$$C=2.125 + 3.729 \times (T),$$

where C is number correct and T is exposure time in seconds. For offsets of 45° and 85° time was reduced by 0.424 and 0.382 seconds respectively (23).

[b] Means collapsed over spacing.

The good prediction obtained in Experiments 2 and 3 raises the possibility of the following clinical use for the test. Each clinical subject's performance under static conditons will serve as his or her own baseline. Then performance in conditions requiring eye or coordinated head and eye movement conditions will be expressed as a percentage of baseline. These percentages can be compared to those generated by normal subjects; if they fall outside the normal confidence intervals (CI) then performance will be considered abnormal. In that case one or more of the oculomotor control systems may be implicated. For example, if performance is normal for the eye movement condition but outside the CI for one requiring coordinated head and eye movement, the function of the vestibular system must be suspect. On the other hand if performance is outside the CI for both movements certain CNS problems may be indicated.

In addition to clinical implications the finding of predictability in Experiments 2 and 3 may have meaning for performance estimation in human engineering. Definitive data are not provided here but there is a very strong suggestion that normal performance on a given task under static conditions can be used to predict performance under conditions requiring eye movement or coordinated head and eye movement for target acquisition. Crucial points are the development of empirical equations to provide an estimate of the average time taken to acquire the target in horizontal and vertical movement and an analysis of individual differences in acquisition time.

Multiple Linear Regression

A multiple regression equation was calculated for performance as a function of exposure time, spacing and offset. As in Experiments 1 and 2, the data are from a factorial design with an equal number of data points in each condition; as a result they are mutually orthogonal and their effects may be considered independently.

The regression equation accounts for a significant amount of the total variance, $F(3,188) = 179$, $p < .001$. The multiple correlation is .860 and 74% of the variance is accounted for by the equation. As in Experiment 2 exposure time accounts for a large part of the variance and is positively related to performance ($r = .839$); offset exerts a smaller negative effect on performance ($r = -.172$); and spacing a still smaller positive effect ($r = .085$). Exposure time and offset account for nearly all the systematic variance with spacing contributing less than one percent.

The regression equation is

$$C = 1.07 + 0.02 \times (S) + 4.15 \times (T) - 0.01 \times (F)$$

where C is number correct, S is spacing in minutes, T is exposure time in seconds, F is offset in degrees and 1.07 is a constant.

The particular values obtained are not as important as establishing the presence of a functional relationship between performance and the three variables under conditions of coordinated head and eye movement. All variables act in the expected directions and together account for a large and significant portion of the total variance.

Patterns of Head and Eye Movement

Head and eye position, and their sum, gaze, were recorded. No recording was made of the occurrence of fixation letters or digit array presentation in relation to head and eye movement. For this reason no measurement of head and eye reaction times can be obtained from the recorded data; instead only empirical information on movement time, extent and velocity are available. Without reaction times no empirical estimates of fixation time are available from the present study.

The patterns of head and eye movement are what might be expected from normal subjects as indicated by previous research (1,12) into a single coordinated head and eye movement. Some examples of the patterns are presented in Figures 7,8,9 and 10. Figure 7 represents the predominant pattern. Head, eyes and gaze are relatively stable before the large shift. There is a large, high velocity saccade of short duration and a slower, longer duration head movement which start at nearly the same point in time. Together they produce a rapid shift in gaze which is normally complete at the end of the saccade. After gaze reaches the target as a result of combined head and eye movement, the eye counterrotates at a rate proportional to that of the head so that gaze remains stabilized while the head continues to turn. As others have noted, head movement generally stops short of the full offset so that the eyes remain displaced in the head by $10^\circ - 20^\circ$ during the digit reading task.

A second pattern is presented in Figure 8. This pattern has been called a "compensatory" movement by Robinson (21,22), who noted its occurrence when subjects had to perform a central task then shift head and eyes to the periphery. The head starts to move before the saccade; the eyes counterrotate, apparently to maintain stable gaze on the fixation letters during the slow anticipatory head movement. At some point a saccade is initiated and the remainder of the movement is like that described above.

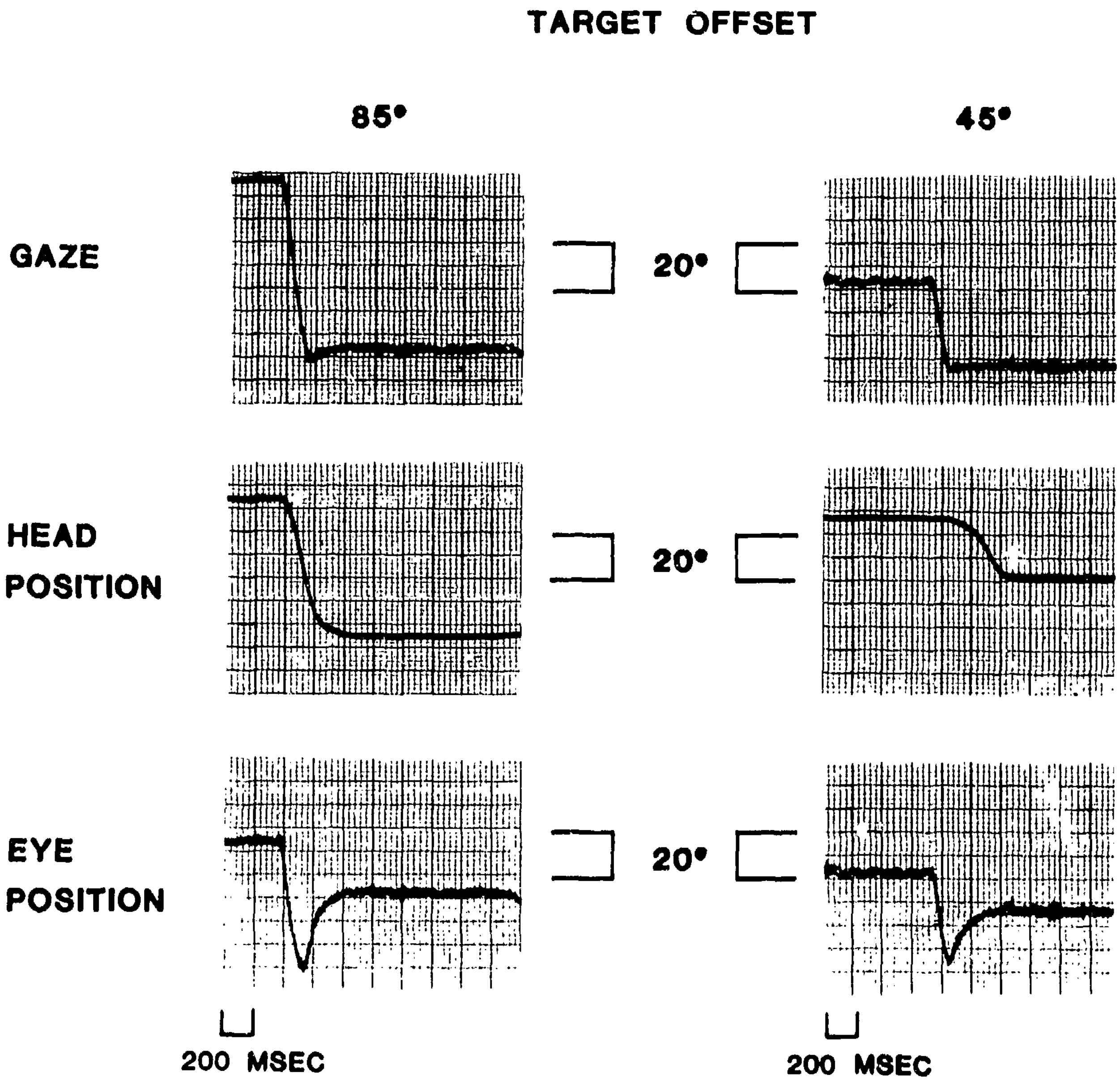

Figure 7

Typical Eye, Head and Gaze Position Tracings for 45° and 85° Offsets, Experiment 3

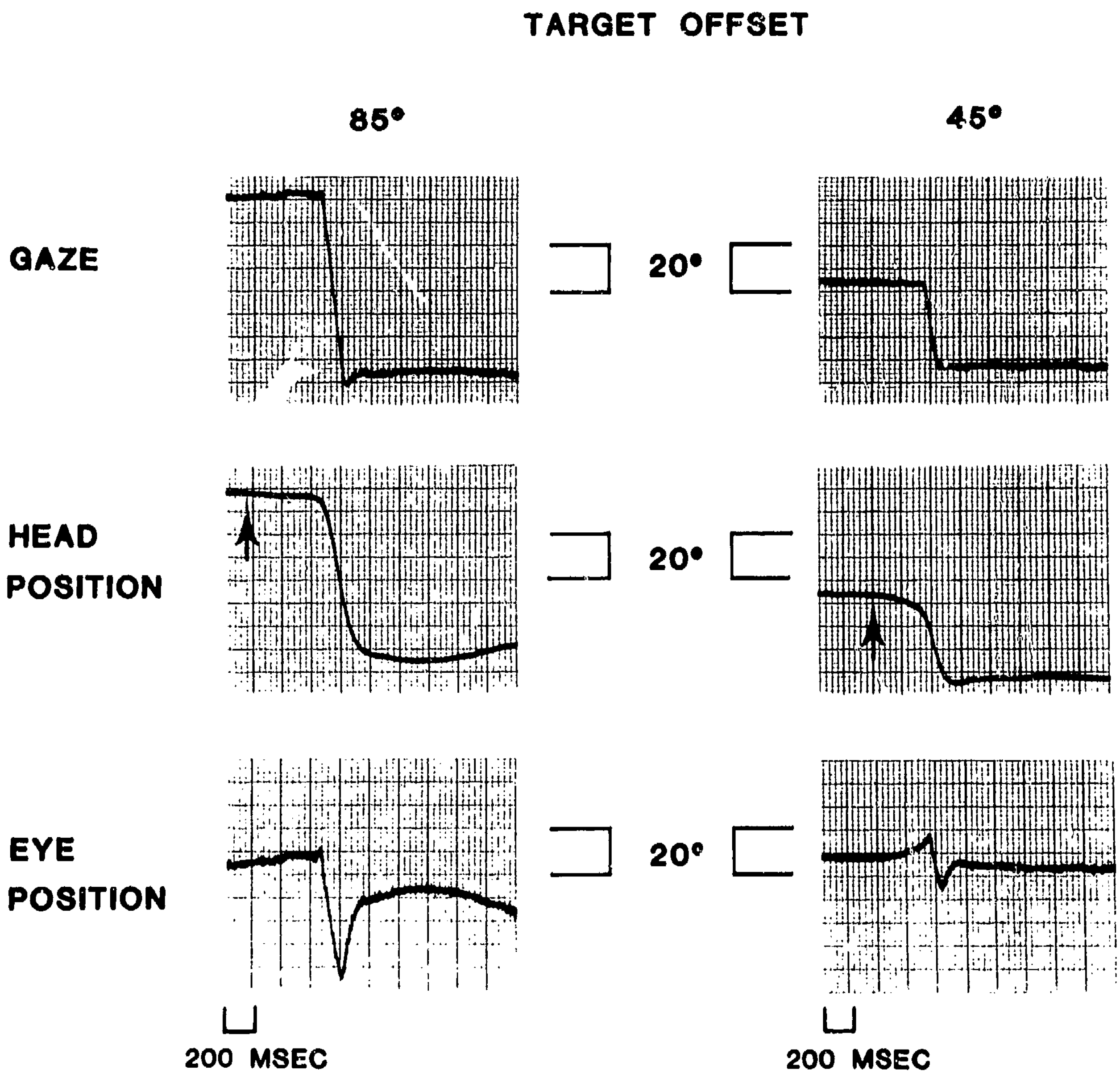

Figure 8

Eye, head and gaze position tracings showing compensatory eye movement prior to the saccade, Experiment 3. Head movement begins first (at arrow on Head Position record) with the eye counterrotating to maintain stable gaze before the eye saccade and the fast head movement start.

Table VI

Description of Eye, Head and Gaze Movement, Experiment 3

Variable		45 Degrees Arithmetic Mean	45 Degrees Standard Deviation	85 Degrees Arithmetic Mean	85 Degrees Standard Deviation
Head	Duration[a]	320	82.8	417	149.7
	Displacement[b]	32.6	7.42	74.7	8.6
	Velocity[c]	122	61.2	207	72.1
Eye	Duration[a]	147	29.8	202	32.3
	Displacement[b]	31.5	6.2	37.3	8.4
	Velocity[c]	246	87.3	203	61.4
	Stop Position[d]	9.7	5.9	9.2	6.5
Gaze	Duration[a]	187	44.4	277	76.1
	Displacement[b]	39.0	1.9	77.7	4.2
	Velocity[c]	236	61.4	308	78.1

[a] In msec.

[b] In degrees.

[c] In degrees/second.

[d] In degrees from start.

Several characteristics of eye, head and gaze movement were manually derived. The reference point for the scoring of head, eye and gaze movement was that of the maximum displacement. For the eye this was the end of the saccade before counterrotation. Head and gaze velocity were calculated over the entire movement while eye velocity was calculated for the initial saccade. To obtain the values in Table VI, five trials were selected at random from the 54 available for each subject at each offset and an average computed for each subject. The means in the table were then calculated over the 12 subjects for which good recordings were available.

In comparing the 45° and 85° offsets, movement duration, displacement and velocity are of interest. Head, eye and gaze duration and displacement are greater in the 85° condition. That is, as target offset increased all relevant movements increased in both size and duration. That the duration of head movement varies with offset in the present experiment appears to run counter to Gresty's (12) finding of invariance with offset. The actual durations are also shorter than that reported by Gresty (450 msec). Differences between testing procedures or accuracy of scoring probably account for this incongruity. One procedural difference is that in the Gresty study, target position was randomized while in the present study the position was known to the subject.

Average gaze displacement falls short of the full target offset by 6° and 7.3° for the 45° and 85° offsets, respectively. It is possible that some of the difference between requested and produced gaze shift is due to the subjects' head position being slightly further from the displays than the instrument used to set up the display positions. If this were to happen the angles at the position of the subject would be reduced and the gaze shifts produced may have been entirely appropriate. Because only relative positions are known it is not possible to determine whether there was a shortfall or whether the angles traversed by gaze were appropriate for the position of the particular subjects' head. Some studies have shown highly accurate, final gaze position while others have shown undershooting. Studies using relatively small, dim targets have found that final gaze position closely matches target offset even though gaze position at the moment of peak eye displacement falls short of target offset (1,5,12). With larger targets there was consistent undershooting for offsets over 60°; the amount of undershooting (7°-10°) was directly related to brightness (23). Target size in the present study is more than twice as large as those used in the set of studies showing high gaze accuracy and one-third of that used in the study showing undershooting. Target luminance in the studies showing high gaze accuracy was about one-third that of the present study. No luminance values were given even though target brightness was varied in the study which showed undershooting (23). The undershooting with large, bright targets and accuracy with small, dim ones suggest that subjects shift gaze just enough to see the target clearly.

If the entire gaze shortfall occurred at the digit array the potential usefulness of this procedure as it currently stands is not necessarily jeopardized. The purpose is not to require the subject's gaze to land directly on the target but rather to test the efficiency of the oculomotor control systems. If gaze is shifted near enough to the array and stabilized so that reading is possible, the systems are by definition working sufficiently. However, the above considerations suggest that test sensitivity could be improved if the digits are reduced in luminance and/or size. This may be desirable for purposes of aviator testing.

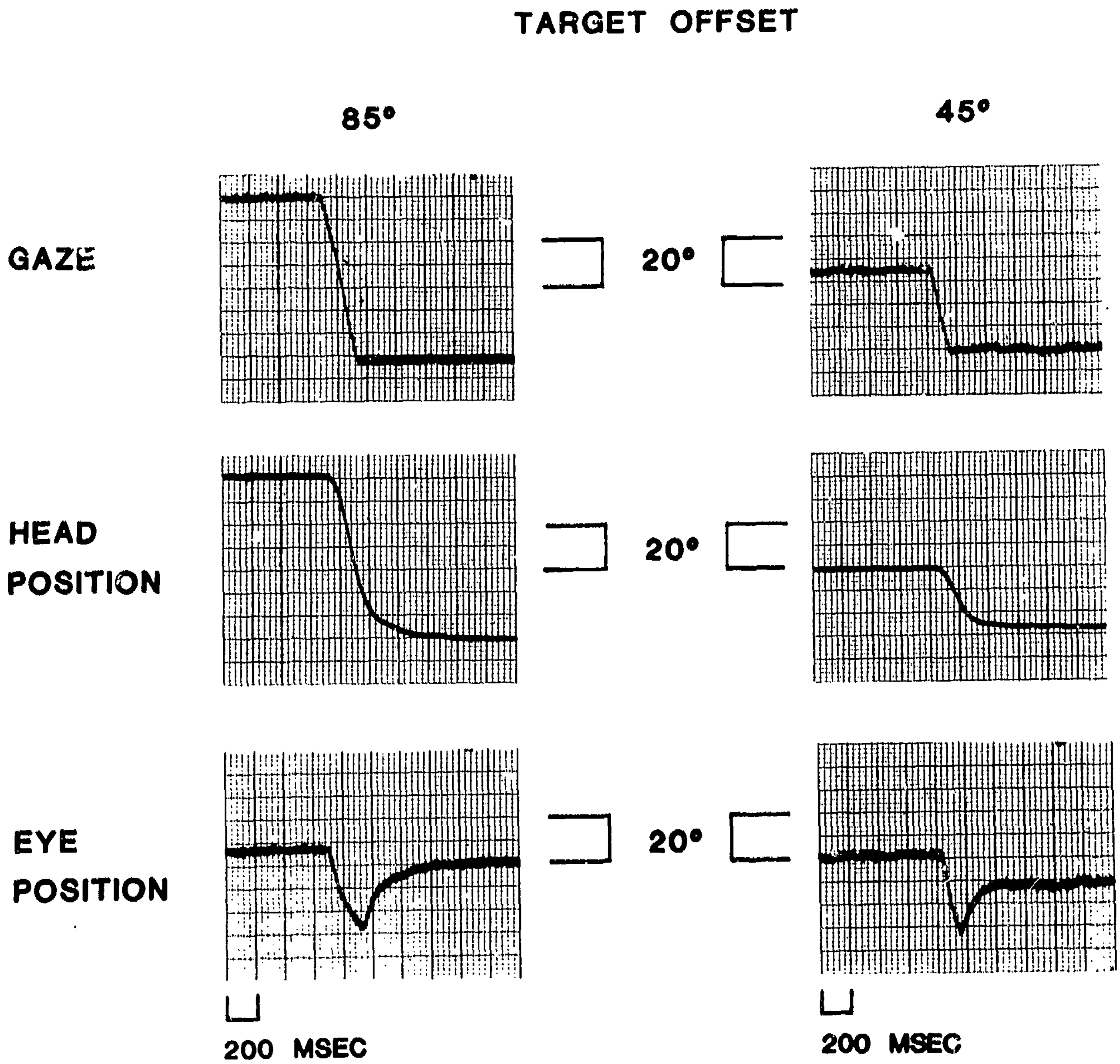

Figure 9

Tracings from Experiment 3 which show a rounded slope (change in eye velocity) during the saccade, most dramatic case. Note step-like change in gaze position, indicating uniform velocity.

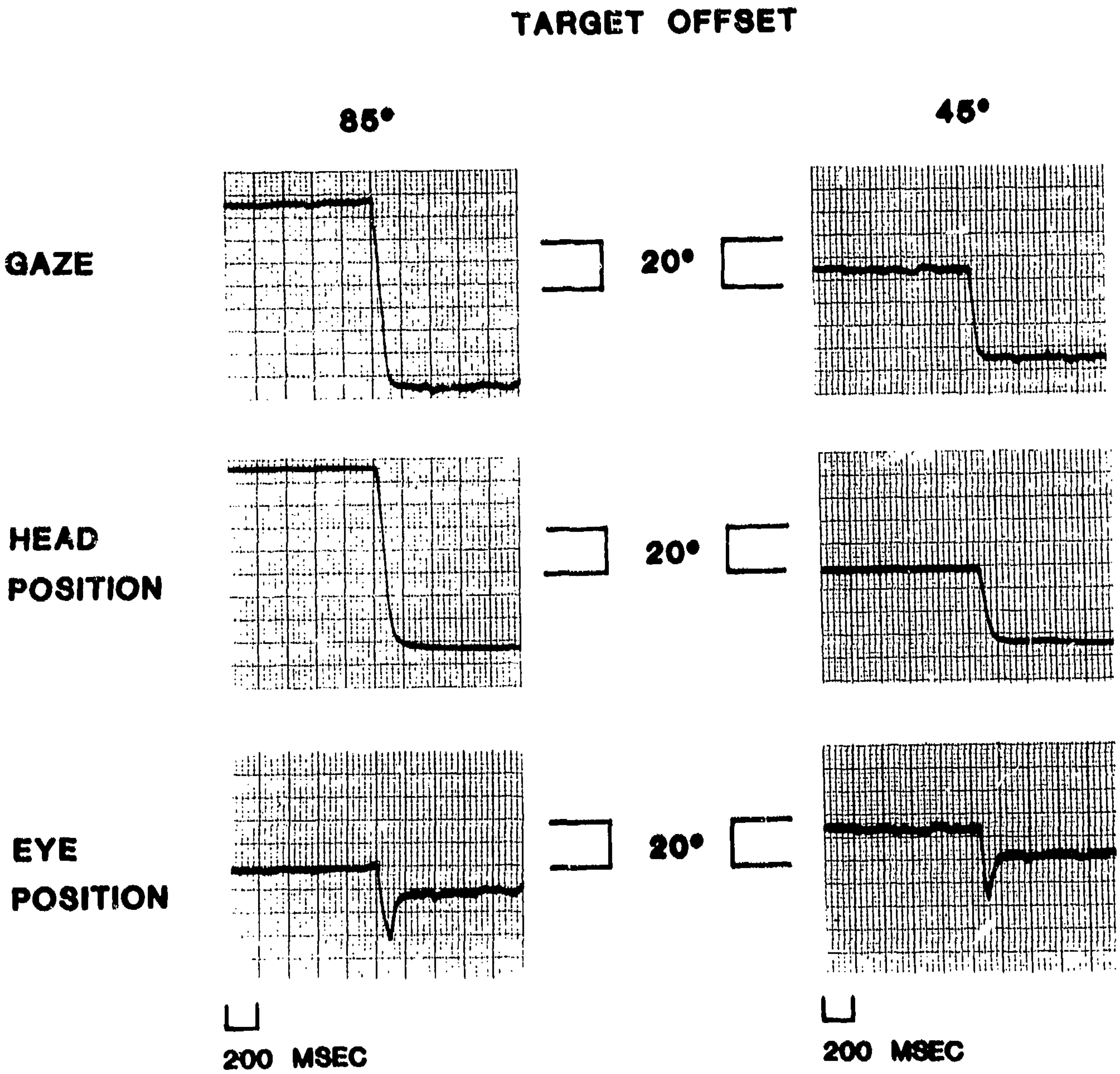

Figure 10

Tracings from Experiment 3 which show a rounded slope (change in eye velocity) during the saccade, typical case. Note step-like change in gaze position, indicating uniform velocity.

Regarding velocity of movement there is a large increase in head and gaze velocity with an increase in offset from 45° to 85°. Despite an increase in eye displacement in the 85° condition, average velocity actually decreases. Eight of 12 subjects show such a velocity decrease for 85°; one subject did not change and three show an increase. Across all subjects the average decrease is 43°/sec. Over subjects there is a significant decline in average eye velocity for the 85° condition, $t\ (11) = 1.95$, $p < .05$ by 1-tailed test. The decrease may be partly explained by considering some previous research along with movement characteristics in Figures 9 and 10. Barnes (1) and Gresty (12) have described a reduction in eye velocity during the saccade that is associated with high velocity head movement. This reduction of eye velocity appears as a "rounding" of the eye position tracings in Figures 9 and 10. In those figures one can see that the change in slope, or velocity, appears to begin close to the time of the onset of high velocity head movement. Examination of the data revealed that in the 45° offset condition only 10% of the saccades examined show this rounding. In contrast, over 50% of the saccades examined in the 85° offset condition show some rounding. On over 90% of the trials both offset conditions demonstrate uniform gaze velocity. This is quite impressive, given the changing head and eye velocities which are summed, moment by moment, to produce it. As Gresty points out, the fact that gaze velocity remains highly uniform over the full gaze shift suggests that the vestibulo-ocular reflex (VOR) is reducing eye velocity at a rate proportional to increasing head velocity. The VOR generated slow phase eye movement, which is in the opposite direction of head movement, is algebraically summed with the high velocity saccade, which is in the same direction as head movement. Not all subjects show this rounding with high velocity head movement, particularly those in which head movement starts first or simultaneous with eye movement. In these cases the VOR generated, slow-phase velocity is probably being summed with saccade velocity throughout the saccade, but again, gaze velocity is uniform throughout the movement.

In the 85° condition there is an average head velocity increase of 85°/sec over that in the 45° condition. At the same time there is an average decline of eye velocity of 43°/sec. The previous discussion suggests that the decrease in eye velocity is produced as follows: 1) head velocity increases in the 85° conditon; 2) higher head velocity produces higher VOR slow-phase velocity which is summed algebraically with saccade velocity, producing a reduction in eye velocity.

To examine some inter-relationships between variables and offset conditions three sets of correlations were computed. Each depends to some extent on variation between subjects, that is on individual differences. The first set of correlations can be used to consider the relationship between dependent measures within offset conditions. These correlations, presented in Table VII, are based on 12 data points; each data point is the average for a single subject. A correlation in this set requires covariation of the two variables across subjects (e.g., a positive correlation between displacement and velocity requires that some subjects show lower displacement and lower velocity while others show higher displacement and higher velocity). The second set of correlations can also be used to consider the relationship between dependent measures, in this case over 45° and 85° offset conditions. These correlations, presented in the third numerical column of Table VII are based on 24 data points; each point is the average for a single subject. Because there are two offset conditions there are two points for each of 12 subjects involved in the calculation. By examining the data for both offset conditions together we are able to extend the range of the dependent variables beyond that which is due to individual differences. Certain relationships may emerge over conditions

TABLE VII

Selected Correlations Among Movement Characteristics, Experiment 3

Variables [a]	Within 45° Condition [b]	Within 85° Condition [b]	Over 45° and 85° Conditions [c]
$Duration_H$ vs. $Displacement_H$	-.3167	-.2588	.2782
$Displacement_H$ vs. $Velocity_H$	.7781**	.5840*	.7113**
$Displacement_G$ vs. $Velocity_H$	.5689	.4629	.6102**
$Duration_E$ vs. $Displacement_E$	-.4619	.1016	.1704
$Displacement_E$ vs. $Velocity_E$	.8444**	.8117**	.5893**
$Displacement_G$ vs. $Velocity_E$	.3551	-.0627	-.2689
$Duration_G$ vs. $Displacement_G$	-.0875	.1248	.6021**
$Displacement_G$ vs. $Velocity_G$	.2594	.0092	.4769*
$Velocity_H$ vs. $Velocity_G$	.3210	.3146	.4947*
$Velocity_E$ vs. $Velocity_G$	.5875*	.6997*	.3830

[a] Subscript H refers to head, E to eye and G to gaze.

[b] 10 degrees of freedom.

[c] 22 degrees of freedom.

* $p < .05$ by 2-tailed test.

** $p < .01$ by 2-tailed test.

which are masked by the truncated range within conditions. There are positive correlations within and over conditions for the relationship between displacement and velocity of the head and eye. There is no such relationship for gaze within conditions, possibly due to a shrinkage in variation (See Table VI), but there is one over conditions. Also over conditions there is a positive relationship between gaze displacement and head velocity similar to that reported previously (1). There is also a positive correlation between head and gaze velocity over conditions.

The third set of correlations allow a consideration of the consistency of performance by providing an estimate of covariation within several key variables over offset conditions, e.g., head velocity at 45° versus head velocity at 85°. Again, the source of variation is in individual differences. The correlations, presented in Table VIII, are based on 12 data points; each point is the average for a single subject. Head and gaze velocity show positive correlations between 45° and 85° conditions. Subjects who demonstrated high head and gaze velocity at 45° offset also show it at 85° offset. Finally, there is a high positive correlation ($\underline{r}$ = .93) between number correct at 45° and 85°, suggesting that subjects who do well at the 45° offset also do well at 85° offset. The consistency of these indices of performance suggest that a test of oculomotor control need only consider coordinated head and eye movement in a given direction to a single offset, e.g., 75°. Performance at other offsets in the same direction will be highly correlated.

SUMMARY

Generally test performance improves with increases in spacing and exposure time and decreases with increases in offset. As in Experiment 2 the effects of spacing and offset are less consistent than those of exposure time. Most of the variance is accounted for by exposure time; offset contributes a small amount and the effect of spacing is quite small. Performance predicted using estimates of gaze delay to estimate time available for fixation closely matched the actual performance. Good prediction from Experiments 2 and 3 suggest that the performance of normal subjects in eye movement and coordinated head and eye movement conditions is quite predictable from static performance for normals. This does not mean that we need not measure the performance of clinical subjects in movement conditions but rather that lower than normal performance in these conditions may reveal deficits in one or more oculomotor control systems.

Patterns of coordinated head and eye movement generally show what is expected of normal subjects. Combined head and eye movement produces a rapid gaze shift; this is followed by gaze stabilization for the remainder of head movement which is produced by counterrotation of the eyes. Some subjects start head movement first with accompanying compensatory eye movement to fix gaze; others keep head and eyes fixed until a rapid saccade is initiated, followed closely by head movement. Average head and gaze velocity increase with increases in offset, while average eye velocity decreases. This decrease in average eye velocity appears to be due to a modification of eye velocity by the onset of high head velocity in the 85° condition. Displacement and velocity are correlated for head, eye and gaze. Eye and gaze velocity are correlated within offset conditions while head and gaze velocity are correlated over offset conditions. In general subjects who show high head and gaze velocity and performance at 45° also show it at 85°.

TABLE VIII

Correlations Between Head, Eye and Gaze Velocities and Number Correct at 45° and 85°, Experiment 3

Variables	Correlation
Head Velocity 45° vs 85°	.8880*
Eye Velocity 45° vs 85°	.5173
Gaze Velocity 45° vs 85°	.7755*
Number Correct 45° vs 85°	.9252*

*$p < .01$ by 2-tailed test for 10 degrees of freedom

COMBINED DATA FROM EXPERIMENTS 1,2,3

The multiple regression analyses from Experiments 2 and 3 suggest a slight inverse relationship between offset and performance. It should be remembered that these analyses consider a limited range within a single type of movement (e.g., eye movement or coordinated head and eye movement). To examine the influence of offset over the full range of movement, selected data from the three experiments were combined. Values for offset ranged from 0 - 85° with data points at 0°, 2.5°, 5°, 45°, and 85°. The data for zero offset came from Experiment 1, that for 2.5° and 5° from Experiment 2, and that for 45° and 85° from Experiment 3. Values for exposure time and spacing that were common to all three experiments were selected. The values were 0.5 and 1.1 seconds exposure time, and 3.5' and 14.2' inter-digit spacing.

With five offsets, two exposure times and two spacings there were 20 unique points. A description of the data at these points is provided in Table IX. For each point there are roughly equal numbers of subjects. The means and standard deviations of performance are plotted in Figure 11. Average performance increases with an increase in exposure time and for wider spacing, and decreases with an increase in offset.

The graphic impression is supported by the multiple regression analysis. The regression equation accounts for a significant portion of the total variance, $F(3,300) = 491$, $p < .001$. The multiple correlation is .911 with about 83% of the variance accounted for by the regression equation.

Table X presents the variance-covariance-correlation matrix in which may be seen the zero correlations between exposure time and offset, and exposure time and spacing. The correlation between spacing and offset is zero to three significant places. When the semipartial correlation coefficients are computed between number correct and any of the three predictor variables, given either or both of the remaining predictors, they are in fact equal to the simple

TABLE IX

Description of the Data from Five Offsets Across Three Experiments for Comparable Conditions of Spacing and Exposure Time

		0.5 sec Exposure					1.1 sec Exposure				
Spacing[a]	Offset[b]	X	SD	Min	Max	N	X	SD	Min	Max	N
3.5'	0	4.16	0.44	3	4.8	20	6.1	0.61	5	7.5	20
	2.5	3.33	0.31	2.8	3.8	12	5.45	0.41	4.5	6	12
	5	3.33	0.49	2.5	4.2	12	5.23	0.50	4.5	6	12
	45	2.88	0.56	2	4.1	16	4.91	0.49	4	5.7	16
	85	1.96	0.64	1.1	3.1	16	4.88	0.63	4.1	5.8	16
14.2'	0	4.0	0.40	3.2	5	20	6.16	0.57	5.3	7.2	20
	2.5	3.57	0.34	3.2	4.3	12	5.91	0.34	5.3	6.3	12
	5	3.48	0.31	2.8	3.8	12	5.44	0.58	4.3	6.3	12
	45	2.98	0.57	1.8	4.1	16	5.42	0.66	4.2	6.2	16
	85	2.41	0.67	1.5	3.6	16	4.95	0.76	3.9	6	16

[a] Visual angle

[b] In degrees

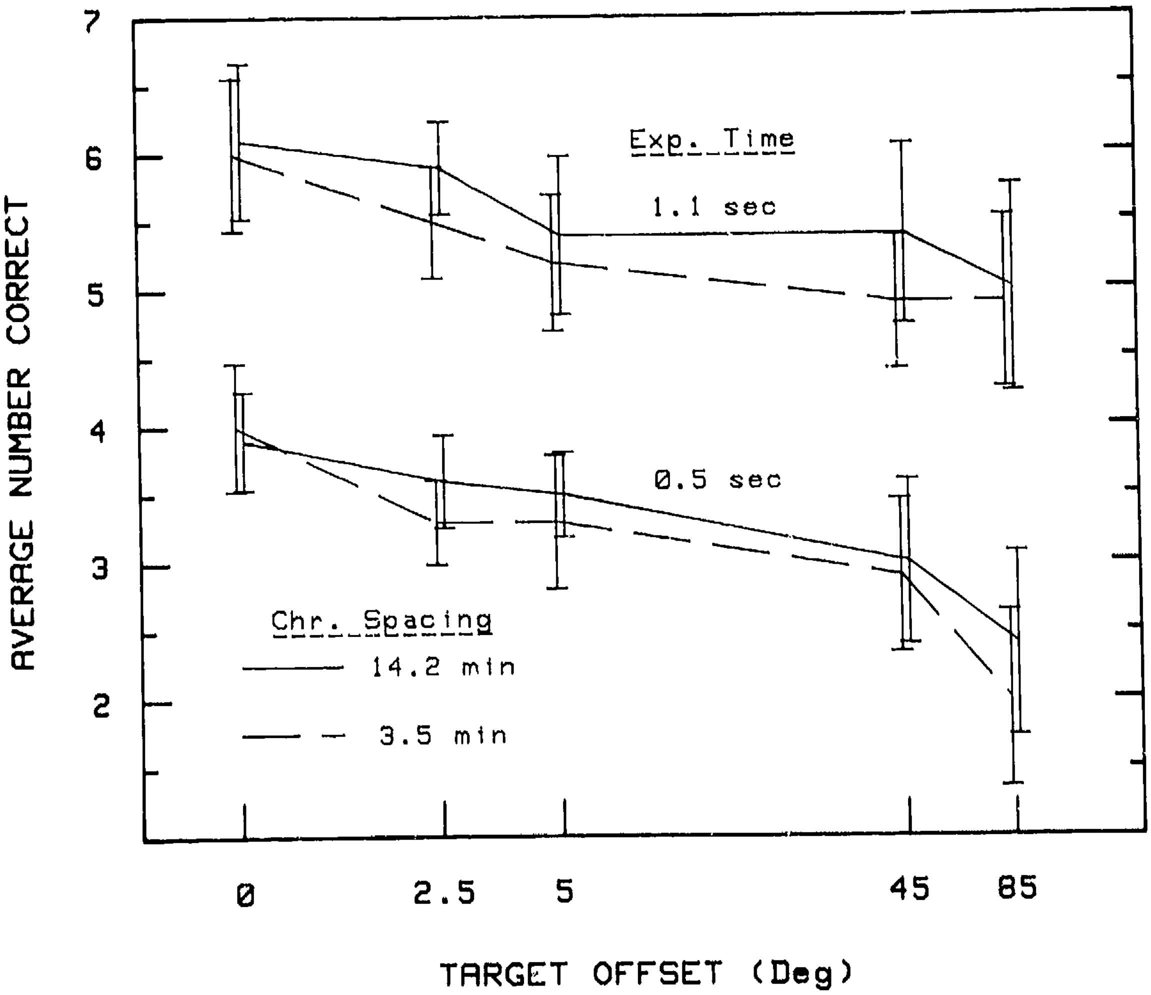

Figure 11

Average number correct (± 1 SD) as a function of offset, spacing and exposure time, combined data from Experiments 1, 2, 3.

correlation between number correct and the single predictor. Therefore, conditional tests of significance are unnecessary. In assessing the relative contributions of the three predictors we may consider them independently.

TABLE X

Variance, Covariance, Correlation Matrix for Combined Data*

	Number Correct	Offset	Spacing	Exposure Time
Number Correct	1.886	-0.416	0.511	0.388
Offset	-.396	0.583	0.001	0
Spacing	.069	.000	28.720	0
Exposure Time	.818	0	0	0.903

*Variances on main diagonal, covariances above and correlations below the diagonal.

The correlation between performance and exposure time is strong and positive (r = .818). Over the range of offset considered here, there is a reasonably strong negative correlation between log (offset + 1) and performance (r = -.396). There is a weak positive correlation between spacing and performance (r = .069).

The general direction of these results as well as the magnitude of the relationships between performance and exposure time and spacing are quite similar to those found in the regression equations for Experiments 2 and 3. However, the magnitude of the relationship between offset and performance is considerably larger when examined over a range of required movement from 0^{o} to 85^{o}.

GENERAL DISCUSSION

The present study has implications for several different areas of research and development. In this section the findings of the present study are discussed with reference to the following: 1) human engineering implications; 2) clinical screening of oculomotor deficits; 3) testing of individual differences in oculomotor abilities. The appendix to this report contains a discussion which will be important for those planning to use a version of this test for areas 2) and 3) above. That appendix includes a discussion of a recommended version of the test, several issues that remain to be addressed, and the next appropriate steps in test development.

HUMAN ENGINEERING CONSIDERATIONS

Of interest here are the predictability of performance and the effect of inter-character spacing at levels above the minimum established human engineering guidelines. To briefly summarize the findings, exposure time, offset and inter-digit spacing generally influenced performance in a predictable way. Performance consistently increased with increasing exposure time, generally increased with wider spacing and decreased with increasing offset from initial gaze position. The effects of spacing and offset within experiments were less consistent than exposure time. With practice there was no demonstration of learning over the test trials. No fatigue effect was demonstrated with as many as 120 test trials.

Although data on eye and head reaction time were not available from the present study, estimates were obtained along with estimates for eye and head travel time from previous research (9,23). When exposure times are reduced by estimates of gaze arrival delay, the regression equation from Experiment 1 predicts performance in the movement conditions of Experiment 2 and 3 quite well. This finding may be important because it suggests that performance requiring coordinated head and eye movement can be predicted from static performance by using an empirical equation to estimate gaze arrival delay. The following are needed to predict performance when changes in accomodation or convergence are not required: 1) an estimate of static performance under identical conditions of size, luminance, contrast, etc.; 2) the offset of the target from the starting position; 3) the empirical equation developed by Robinson et al., to estimate gaze arrival delay (23). Of course this applies only to the predicition of average performance of young, healthy adults and not to that of clinical subjects.

A second point of potential significance is the effect of inter-character spacing on performance. The minimum spacing required by MIL-STD-1472B (17, p 93, Section 5.5.5.9) is one character stroke width. The present study used a minimum spacing of four character strokes and a maximum of 16. When no movement is required to acquire the array there is no effect of spacing; moreover, the actual values obtained are nearly identical. In contrast there is a significant advantage for a wider spacing when eye or coordinated head and eye movement are required to acquire the target. The difference between narrow and wide spacing is small, nevertheless it does suggest that numerical information can be acquired more quickly with an inter-character spacing well above the minimum standard. A seemingly related finding was reported by Barnes et al. (4) who showed that reading performance during whole-body angular acceleration improves with wider inter-character spacing or narrower stroke-width.

Together the findings of the present study along with those of Barnes et al. suggest that the minimum standard for inter-character spacing should be reconsidered for situations involving motion and a demand for rapid information acquisition. These situations include those involving fast, natural head and eye movement to acquire information from spatially separated points as well as those encountered in more unusual environments such as aviation. One example of the latter situation is that of vibration of the aviator's head at a frequency (1 - 10 Hz) which produces small involuntary eye movements. These eye movements introduce relative motion between the display and the observer's eye, cause the display to appear blurred, and reduce visual performance (4,6).

The performance difference between the narrow and wide spacing in the present study was small. One might expect that the difference would increase if the narrow spacing were reduced to the required minimum of one stroke-width. However, the difference might be so small as to make no practical difference in most situations. Future research should map out the change in performance as spacing varies between one stroke-width and a full character width for several standard stroke widths. With this information the display designer can consider trade-offs between inter-character spacing, cost and size constraints imposed by a particular display requirement and performance requirements. At the present time the available evidence suggests that for any given stroke-width, reading performance will be better with inter-character spacing considerably above that recommended by military standards.

CLINICAL SCREENING OF OCULOMOTOR DEFICITS

The simple action of redirecting gaze requires several significant coordinated actions to produce adequate visual performance. A high velocity saccade must be generated which places the desired image upon the retinal region of greatest sensitivity. If this end is not achieved initially, then corrective saccade(s) are required to enhance visual performance. Saccadic control is subject to a number of central nervous system (CNS) dysfunctions, including longer saccade reaction time, low saccade velocity and multiple-step, hypometric saccades (15).

The test procedure developed in the present study is based on a brief, precise exposure of the visual stimulus to the subject. Visual performance, in turn, is powerfully and lawfully related to the stimulus exposure time. All of the deficits mentioned above will act to reduce the amount of time available for fixation in conditions which require eye movement only. The test procedure, possibly with appropriate modifications to improve sensitivity[a], will be sensitive to the CNS disorder(s) producing multiple-step hypometric saccades because the time to make a corrective saccade is relatively great. It may also be sensitive to disorders producing longer response latencies and lower saccade velocity.

Healthy saccade and vestibular systems interact to produce a rapid, step-like gaze shift that is normally complete at the end of the saccade and is stable during the remainder of head movement. Labyrinthine damage affects the ability to perform this coordinated movement by causing an overshooting of the target or a "rounding" of the gaze shift rather than the normal step-like shift (28). Overshooting requires a corrective saccade while "rounding" is associated with a slower shift. Examples of the time beyond normal for overshooting and rounding are 750 msec and 400 msec respectively (28, Figure 1, p 573). The test procedure described in the present study was sensitive to as small a difference as 300 msec in exposure time[b]. Therefore, it is expected that it will be quite sensitive to time delays as great as those above caused by labyrinthine damage.

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[a]The Appendix to this report contains a discussion of test sensitivity.

[b]The test may be sensitive to smaller differences in exposure time but 300 msec was the smallest one tested.

Following unilateral damage both abnormal gaze shift patterns (rounding and overshooting) have been found to occur almost entirely ipsilateral to the damaged ear (28). Recovery takes as long as six months. It seems possible that the test procedure may be able to isolate the damaged ear because performance will be normal for gaze shift in one direction, but will be down substantially for the other direction. Following bilateral damage both abnormal gaze shift patterns occur for movement in both directions (28). Recovery here takes as long as nine months and sometimes never occurs. Performance on the test would be expected to be worse than normal for movement in both directions. Such performance would tend to differentiate unilateral and bilateral patients.

From a clinical research perspective it might be quite informative to investigate performance improvement during the recovery from labyrinthine damage. Of particular interest is the rate of improvement and the time, if ever, that performance becomes functionally normal.

Another research question of interest is that of the relationship between objective and subjective measures of degraded vision among CNS and vestibular patients. Recently Wist et. al. (32) have shown that with adaptation to peripheral eye muscle disorders, subjective oscillopsia produced by 1 Hz head oscillation diminishes even though inappropriate eye movements persist. A similar adaptation to persistent visual problems has been reported in patients with labyrinthine damage (13). These reports suggest that in some cases CNS compensation reduces the disturbing, subjective apparent motion symptoms. One interesting area for further research is whether this subjective decrease in blurring is paralleled by an objective increase in performance on a test of oculomotor control like that described in the present report.

INDIVIDUAL DIFFERENCES IN OCULOMOTOR ABILITIES

As mentioned above, the pilot and other aircrew members must scan the cockpit instruments to perform a variety of tasks necessary to satisfy mission requirements. Tole, et. al. (26) have shown that highly skilled pilots' scanning behavior is less affected by an increase in cockpit workload. Of particular interest to the present discussion is whether this behavior remains relatively stable partly because of more efficient oculomotor control systems. If it does, then a performance-based test procedure similar to that described in the present report might be useful in pilot selection.

There is evidence of variation between subjects in the present study. Table VI shows that the standard deviations for velocity at 45° offset were 61°/sec, 87°/sec, and 61°/sec, for head, eye, and gaze, respectively; at 85° offset they were 72°/sec, 61°/sec and 78°/sec. Schmidt, et. al., (24) have shown that there are relatively large individual differences in peak eye velocity for a saccade of a given amplitude; moreover, variability increased with amplitude. The standard deviation of performance on the test was just over ½ a digit within individual offset spacing and exposure time conditions (See Table IX).

In a human engineering study, Robinson, et. al. (23) fit their average data with an empirical equation to predict the time lost due to gaze arrival delay as a function of target offset. That equation fit their data very well and was usefully applied in the present study. From a systems viewpoint, the prediction of average performance is adequate and appropriate. But with respect to pilot selection, it might be desirable to select those people with the most efficient oculomotor control systems, that is, those able to move gaze quickly and to stabilize it for information acquisition.

The present study has reported on a test procedure that, with suitable revision to make it more sensitive*, may be appropriate for testing the efficiency of the oculomotor control systems. The next step is to demonstrate some relationship between oculomotor efficiency and instrument scan ability among skilled pilots. If oculomotor efficiency and scanning behavior are correlated to some extent then the revised test procedure should be considered as a possible tool for use in pilot selection.

*A discussion of these revisions is presented in the Appendix to this report.

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APPENDIX

APPENDIX

RECOMMENDED VERSION

Trial Structure

The trial should be structured the same as in the present study (See Figure 1). Two to four fixation letters should be presented each for 0.2 seconds with 0.2 seconds of blank display between them. This number and timing arrangement keep the subject's gaze at the desired starting location without hindering later performance on the digits.

Spacing

Generally the test is sensitive enough to pick up differences here but there is some lack of consistency. Future versions of the test need not include spacing as a variable. The recommended amount of inter-digit spacing is the more sensitive, narrow spacing from the present study. This is a 3.5' visual angle for a character width of 14', or 1/4 character width. This is above minimum human engineering requirement yet small enough to require stable vision for accurate performance.

Exposure Time

Only one exposure time is needed for defining performance. It must be long enough so that gaze easily reaches it under the most time consuming condition of coordinated head and eye movement. For the purpose of obtaining accurate test results some values above and below the test value should be presented in a randomized sequence. This prevents the subject from adopting an idiosyncratic strategy favoring a particular exposure time. For example, performance at short exposure time is best when the subject tries to take in as many digits as possible before the vocal response. For long exposures a good strategy is to read several letters aloud then to briefly stop vocalization during a scan of the remaining few. Randomly including several "catch" values shorter and longer than the test value along with a required mode of performance (see below) should prevent the subject from adopting an idiosyncratic strategy and will keep performance between subjects more uniform.

It is recommended that the test value be 0.6 seconds with a minimum of six valid test trials at this exposure time. The catch trials should be randomly selected from a range of values above and below the test value. For 0.6 seconds it is recommended that these ranges be 0.2 to 0.4 and 0.8 to 1.0 seconds. Not only will this variation prevent idiosyncratic reading strategies, it should also keep the subject's self-imposed oculomotor demands at a high level. The short exposure times are adequate for performance without movement, but not with movement. Therefore the subject places a high level of demand on his or her oculomotor systems to try to acquire the array. About 0.38 seconds is required for coordinated head and eye movement so that random variation in times greater than that act to prevent the subject's adoption of an idiosyncratic strategy. There should be a few more total catch trials than test trials with the number divided evenly above and below the test value. To get six valid test trials, it is recommended that eight be presented along with 10 catch trials for a total of 18. To provide adequate practice there should be an additional 8 trials at each offset with the exposure time randomly selected from 0.2 to 1.0 seconds. Two trials should be presented from each 0.2 second interval within that range.

Instruction and Practice

Subjects should be instructed to read the digits one at a time, and not to group them (see GENERAL PROCEDURE). It is recommended that they be given about 24 trials of digits-only, followed by 8 more involving the combined task of fixation letters and digits. Equal numbers from each of the 0.2 second intervals mentioned above should be presented in a random sequence. After this initial practice they should perform the 26 trials recommended above for practice and test in each offset condition.

Offset

Baseline data is gathered at zero offset, that is when the fixation letters and digits are presented at the same spatial location. It is recommended that other offsets be used such that one is within the comfortable range of eye movement and the other requires head and eye movement. These offsets should be 15° and 75°, respectively. Fifteen degrees is within the range of comfortable eye movement, while 75° clearly requires both head and eye movement.

For the purposes of identifying individual differences related to visual scanning and to provide human engineering data it would be appropriate to consider movements to both right and left and up and down of both 15° and 75°. For clinical testing some of these may be eliminated if an appropriate testing sequence can be developed. Unilateral CNS lesions may cause saccade abnormalities in one or both directions. Therefore the ability to present stimuli requiring movement in both directions is needed. Bilateral damage to the horizontal canals will reduce performance to either the right or the left, but unilateral damage will show a directional difference. The recommendation for clinical use then is for the ability to test 15° and 75° movement to the right and left, and up and down. An appropriate testing sequence should be worked out so that the actual conditions used may be tailored to the particular clinical subject. This should reduce the time required for clinical testing.

Stimuli Arrangement

In the present study the digits were presented in a horizontal array. Eye movement and coordinated head and eye movement was also horizontal. For this movement orientation instability of gaze would most likely be primarily horizontal. For such instability a horizontal arrangement would be most sensitive. It is recommended that for horizontal movement an arrangement like that in the present study be used.

For vertical movement gaze instability would be vertical, so that the most sensitive arrangement would be one of a vertical digit array. With a horizontal arrangement the subject always shifts gaze to the left of the array and reads from left to right. For many people this is a well learned habit. For vertical movement it is recommended that a second common habit be used, namely that of reading from top to bottom in a column. The vertical digit array should be arranged so that the subject always moves gaze to the top of the array and reads down.

ISSUES TO BE ADDRESSED

Alternate Stimuli Arrangement

In the preceding section a recommendation was made for horizontal and vertical arrangements of the digit array. There are two primary advantages to these arrangements. The first is that they are well-learned, thereby reducing the amount of practice required to learn the digit reading task. The second is that only two baseline conditions (zero offset) are required in the recommended version, one for left-to-right reading and one for top-to-bottom reading. Despite these advantages there may be a problem here. In Experiment 2 there was a directional difference favoring movement to the right. Two possible reasons for this difference were suggested. One is that movement to the right is more accurate. The other is that passing over the digit array in movement to the left causes some smearing of the array within the visual system.

This issue needs to be considered in further research. If performance is reduced by smearing then an alternate stimuli arrangement should be considered. In this arrangement the task of the subject is modified along with the positions of the array so that the subject always shifts gaze to the nearest digit and reads in the same direction as the gaze shift. This is illustrated in Figure A1 of this appendix along with the recommended test version. For gaze shift to the left, the subject reads from right to left, for gaze shift down, the subject reads top to bottom, etc. In this way no digits are passed over to acquire the starting point for reading.

Potential difficulties exist here regarding practice and baseline conditions. The recommended version makes use of well-learned reading habits, while the alternate version makes use of these for gaze shift rightward and downward. Upward gaze shift requires reading from bottom to top and leftward shift from right to left. The latter directions are not nearly as common and as a result may require more practice to stabilize performance before testing. Just how much more practice needs to be established if this alternate arrangement is to be used. A second potential difficulty is that of baseline or zero offset performance. Because four directions of reading are used, baseline performance must be evaluated for all four. This requires twice as many baseline conditions as the recommended version.

Test-Retest Reliability

An important point in the development of any test is the establishment of test-retest reliability. For this particular test the question is the following: given that a person's health does not vary over some time interval, is performance stable during testing on several occasions. Across [illegible]s one would like to observe a high correlation between test performance on several occasions separated by some interval of time. This research needs to be done as part of the normative data collection described below.

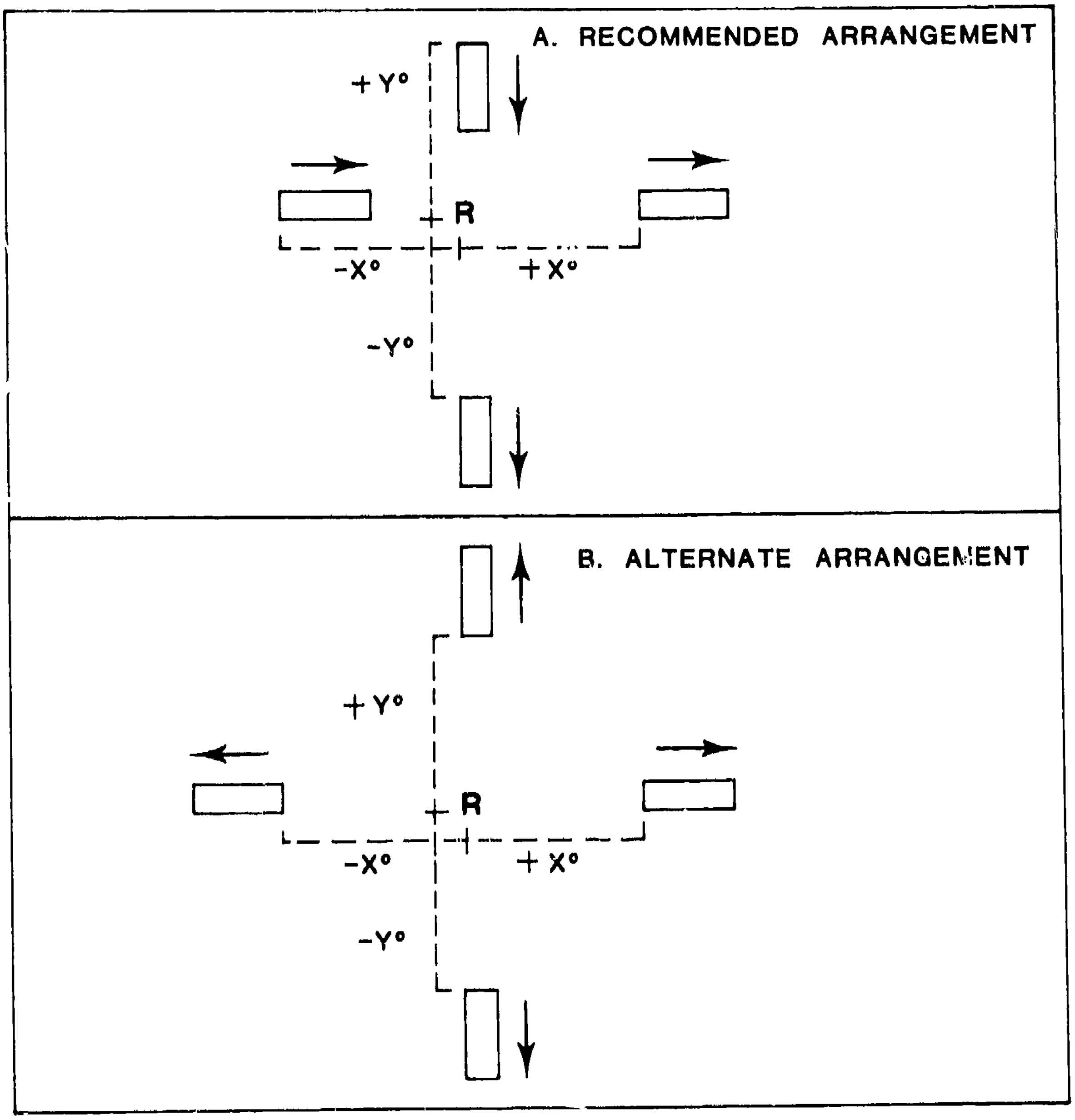

Figure A-1

Recommended (A) and alternate (B) stimuli arrangements for horizontal and vertical gaze shift. Starting position for both is the letter "R" where fixation letters are presented. Movement is from that point to the end of the broken line. Reading direction for the digit array is indicated by the arrows.

Test Sensitivity

The description of the gaze shift in Experiment 3 showed that measured gaze generally fell short of the full shift by several degrees. It is possible that some of the measured shortfall is actually due to the head and eyes being slightly further from the display than the device initially used to determine the angles between displays. It is not known whether the measured shortfall was due to this or to gaze actually starting and/or stopping short of the requested endpoints. A review of related research suggested that gaze will fall short of a large, bright target but will not when it is small and dim. Further research needs to be conducted using the test procedure at the present levels of size and luminance in which the position signals are referenced to the end-points of movement. If gaze continues to fall short of the target a smaller size of character, with an appropriate adjustment of spacing, or a lower level of luminance or both should be considered. This would demand greater accuracy of gaze shift and might make the test more sensitive to individual differences in scan ability.

It is not clear that this change would improve clinical sensitivity to deficits in oculomotor control systems. If gaze is close enough to read the digits then these systems are working adequately. If however more than one major saccade is needed to reach the display, performance will be reduced dramatically because of a decrease in time available for fixation, and one or more of the systems would be suspect.

REQUIRED STEPS FOR TEST USE

Normative Data Collection and Analysis

After modifying the test to allow flexibility in test delivery, scoring, etc., normative data should be collected on young, healthy adults. About 30 should be tested using the recommended test version with horizontal and vertical array orientations and offsets. Both orientations should be used to gather data on baseline or zero offset performance. The horizontal orientation should be used to gather data at 15° and 75° right and left. The vertical orientation should be used for 15° and 75° up and down.

A convenient order for practice and test trials at all offset conditions should be developed. Given the current equipment situation all of the practice and test trials for a given offset condition should be presented in a single block of trials. The order of presentation for the different offsets should be randomized over subjects with the following constraint. All of the horizontal practice and test conditions should occur in one half of a test session and all of the vertical practice and test conditions in the other half. The order of presentation of vertical and horizontal conditions should be counterbalanced over subjects. The analysis should include a test of order effects. If they exist, an order should be selected for normative data collection. Of course this order would also be used for clinical testing.

The distribution of performance in each condition should be described with the usual statistics (e.g., mean, median, standard deviation, skew). Frequency and cumulative frequency distributions should be plotted for graphical interpretation.

For each subject the decline in performance for all non-zero offsets should be expressed as a percentage of baseline or zero offset performance. The distribution of these declines should also be statistically described including the establishment of confidence intervals for these values. It is these confidence intervals against which subsequent patient groups will be compared.

Finally, at least half of the original normal group should be retested on at least one occasion. Descriptive statistics and test-retest correlations should be computed to examine the reliability of the test.

Assessment of Patient Groups

Two patient groups need to be considered here. Both should be tested at all the offsets described above, and head and eye movements should be measured at test time to confirm the diagnoses. Each subject's performance should be compared to the confidence intervals derived from the normative data. In addition, if enough data exists the patient distributions should be statistically described.

The two patient groups are those diagnosed as having oculomotor control deficits of neurological origin and those having deficits of vestibular origin. The neurological patients include those displaying low velocity saccades, saccadic dysmetria or both. The vestibular group includes those with recent labyrinthine damage. Note the word "recent" because those with unilateral damage may adapt to the loss within a month. Those with bilateral damage may require nine months or more even in younger individuals.

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Dr. Percival was a National Research Council Postdoctoral Research Associate when this research was conducted. He is now with IBM Inc., P.O. Box 12195, Department E04/B002, Research Triangle Park, N.C. 27709 Requests for reprints should be sent to Dr. F.E. Guedry, NAMRL, NAS Pensacola.

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Acquisition of visual information from spatial points disparate enough to necessitate head and eye movement involves the vestibular and other oculomotor control systems in shifting and stabilizing gaze relative to those points. In the present study a simple procedure to test oculomotor abilities was developed and evaluated; it uses performance to establish initial gaze position and to insure the required gaze shift and stabilization are rapidly produced. Performance in three experiments was consistently and powerfully influenced by stimulus exposure duration, and to a lesser extent by the size

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) of the required gaze shift. The performance of normal subjects in eye movement and head-and-eye movement conditions is quite predictable from static performance of normals. There were two main conclusions: 1) The powerful effect of exposure time on performance suggests that the procedure will be sensitive to certain types of central nervous system and vestibular pathology. 2) Variation in performance characteristics implies that the procedure may be sensitive to individual differences in oculomotor abilities.