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INTERACTIONS OF THE HORIZONTAL AND VERTICAL HUMAN OCULOMOTOR SYSTEMS: THE VERTICAL SMOOTH PURSUIT AND HORIZONTAL SACCADIC SYSTEMS[1]

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INTRODUCTION

IN A previous paper (FEINSTEIN and WILLIAMS, 1971) the relationship between the horizontal and vertical saccadic systems was examined. Results indicate that the two orthogonal saccadic systems share a common information processing channel. The series of experiments which are discussed in this paper, are intended to investigate the relationship between the horizontal saccadic and the vertical smooth pursuit system. Since the saccadic system responds to non-predictive aperiodic stimuli and the smooth pursuit system responds to continuous predictive stimuli (RASHBASS, 1961; ROBINSON, 1965), a combination of these two forms of stimuli was used.

METHODS

The apparatus used to measure eye movements was the same as that reported on in FEINSTEIN and WILLIAMS (1971). To investigate the relationship between the horizontal saccadic and vertical smooth pursuit system, a predictive random paradigm was chosen. The smooth pursuit system will respond only to the predictive part of the input (assuming that no error correcting saccades are required) and the saccadic system will respond only to the random part of the input. The target velocity can be controlled by using triangular waveforms for the predictive input. The target velocity is a linear function of the triangular input frequency. Since the smooth pursuit system is sensitive to the target velocity, whereas the saccadic system is sensitive to the target position (RASHBASS and WESTHEIMER, 1961), the smooth pursuit system alone can be utilized, provided the target velocity is properly chosen. If random horizontal steps are superimposed on the predictive vertical input, saccades will be evoked from the horizontal saccadic system. By varying the target velocity, one can obtain a function which relates the orthogonal smooth pursuit system and the saccadic system.

The predictive random paradigm consisted of a triangular waveform for the vertical input and a random step for the horizontal input. The displacement of both the horizontal and vertical inputs was ± 5 deg from the primary position of gaze. The target moved vertically up and down at a fixed velocity, with randomly occurring horizontal steps 1·3 sec in duration superimposed on the vertical motion. A typical target presentation consisted of target motion up and down at the primary horizontal position of gaze. The vertical motion was continued for 1·3 sec after a 5-deg step to the right. The target then returned to the center horizontal position, while vertical target motion was continued throughout. After a cycle time of approximately 4 sec another random horizontal step occurred. The vertical input was present at all times during an experimental run. Each occurrence of a step constituted an experimental trial; 30 such trials comprised an experimental block of trials.

The data for this experiment were obtained from three male subjects, J.H., J.M., and W.O., ranging in

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age from 19 to 21 years. Each subject was run through 6 groups of 5 blocks, each group being given on a different day. Each block of trials had a different value of vertical target frequency. The frequencies were (in Hz): 0·1, 0·2, 0·3, 0·4 and 0·5. The first group of trials served to familiarize the subject with the apparatus and the experimental paradigm; no data were recorded for this group. In each of the remaining 5 groups of blocks, the initial 10 trials of each block were used to acquaint the subject with the paradigm, and the remaining 20 trials were recorded and used as data. The subjects were instructed to follow the target as accurately and as quickly as possible. The subjects participated in other experiments on the days in which these data were taken. All data for the subjects were obtained over the same time period.

Three quantities were recorded for each trial: frequency, RT and phase. RT was defined as the reaction time to the horizontal target step. The phase was defined (as shown in Fig. 1) as the relative vertical position at which the horizontal step occurred. Since the vertical and horizontal inputs were not synchronized, the phase was a random quantity. The raw data was processed by taking all blocks of the same frequency for each subject and determining the average RT and the standard deviation. In addition, the trials were processed by sorting them into bins 30 deg in width as a function of phase. Using a computer, the following calculations were made for each such bin: the number of points lying within that bin, the average value of RT over that bin, and the standard deviation for that bin.

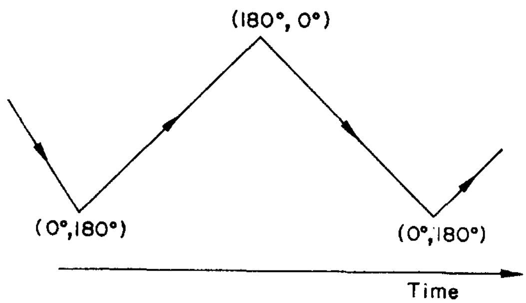


FIG. 1. Diagram illustrating definition and measurement of phase. Phase was measured as the relative vertical position at which the superimposed horizontal step occurred. The above illustration shows that starting on the left bottom, the phase starts at 0 deg. Proceeding up and to the right, the peak is defined as 180 deg. As soon as the target starts its descent, it is regarded as being at 0 deg and proceeding to 180 deg at the bottom. This definition of phase does not take into consideration any differences in oculomotor performance which may exist between upward and downward eye movements.

In addition to the above experiment, an identical experiment was performed in which both the stimuli were in the horizontal plane. This was done to better enable the horizontal–vertical results to be related to previous results in the horizontal plane.

RESULTS

A typical recording obtained using the predictive/random paradigm is shown in Fig. 2. The variables—RT, frequency, and phase—are illustrated in this figure. Figures 3(a–e) represent plots of the averaged data for the three subjects for the 5 values of frequency used. Since peak to peak vertical target displacement was 10 deg, 0·1 Hz represents a target velocity of 2 deg/sec and 0·5 Hz represents a velocity of 10 deg/sec. Each point of these plots represents the average of at least 15 experimental trials. It can be seen from the figures that the results for the 3 subjects are similar, the only significant difference being in the subject's mean reaction time, as shown in Fig. 4.

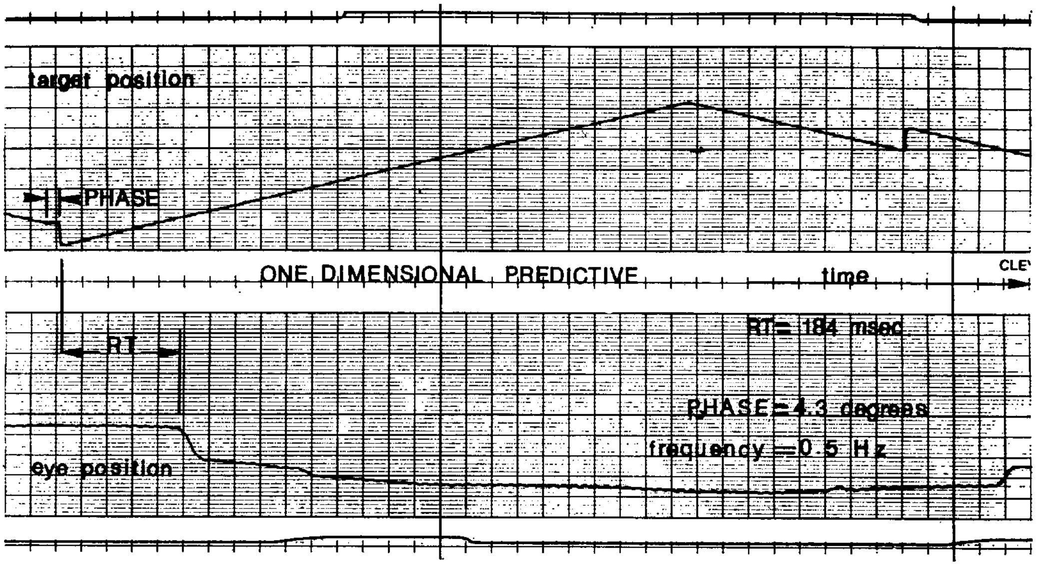


FIG. 2. A typical recording obtained using the Predictive/Random paradigm. The target position recording represents the superposition of the vertical triangular target and the 5 deg randomly occurring horizontal step. The measurement of phase is indicated. The eye position tracing shows the definition and measurement of RT. Note, the upper and lowermost tracings have no meaning for this experiment.

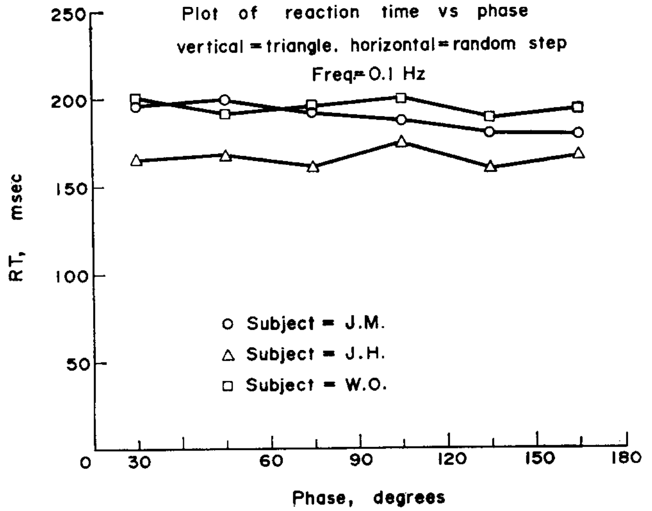


Fig. 3A

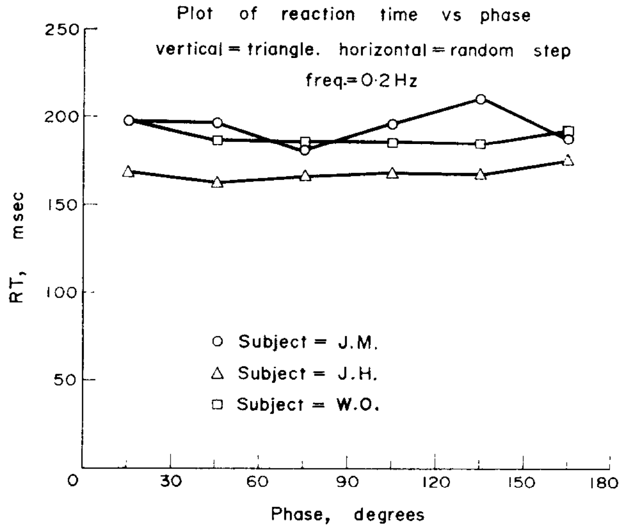

Plot of reaction time vs phase
vertical = triangle. horizontal = random step
freq.= 0·2 Hz
250
200
150
100
50
0
RT, msec
○ Subject = J.M.
△ Subject = J.H.
□ Subject = W.O.
30
60
90
120
150
180
Phase, degrees

Fig. 3B

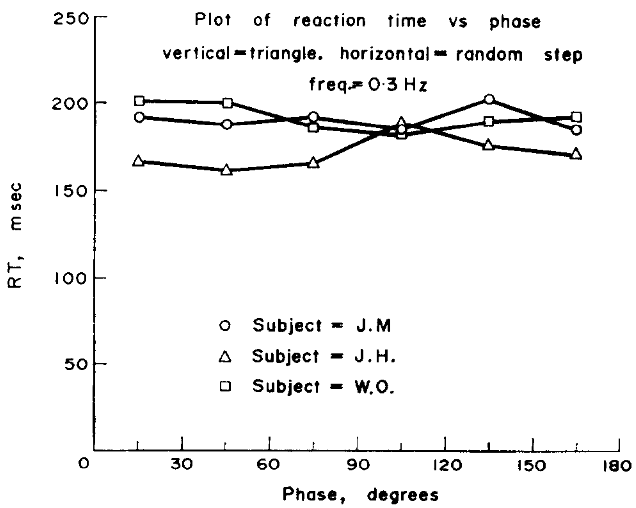
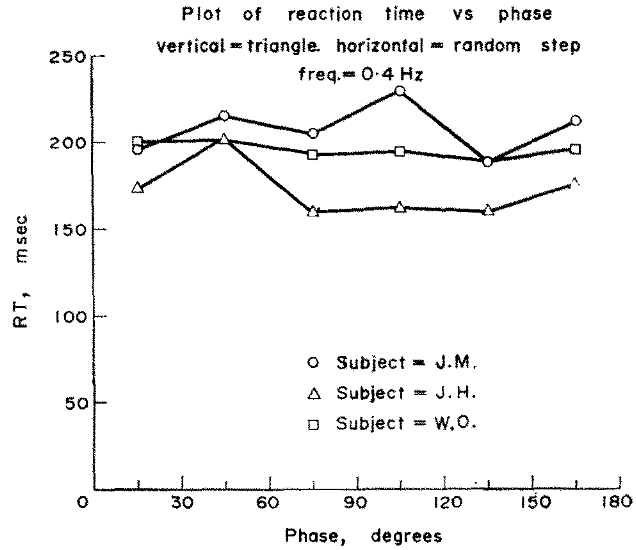

Plot of reaction time vs phase
vertical = triangle. horizontal = random step
freq.= 0·3 Hz
250
200
150
100
50
0
RT, msec
○ Subject = J.M
△ Subject = J.H.
□ Subject = W.O.
30
60
90
120
150
180
Phase, degrees

Fig. 3C



Fig, 3D

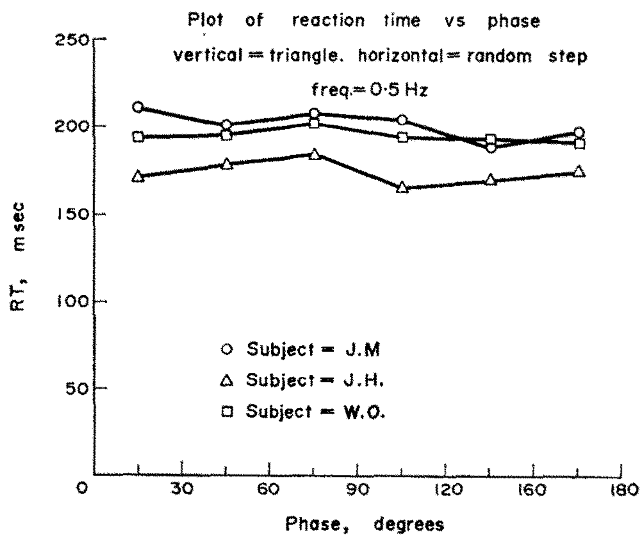


Fig 3E

FIG. 3. Plot of Reaction Time vs. Phase: Target Frequency as a Parameter. Figs 3(a–e) are plots of RT vs. phase for vertical target frequencies of 0·1, 0·2, 0·3, 0·4 and 0·5 Hz respectively. These frequencies represent 2, 4, 6, 8 and 10 deg/sec respectively. The results for the three subjects are shown. Each point represents the mean value of RT over the corresponding 30 deg of phase. The points are plotted at the centers of these 30 deg bins. The symbol table is given for each plot and the symbols are consistent with those used in the other figures. It is apparent that there is little if any relationship between RT and phase at any of the target frequencies.

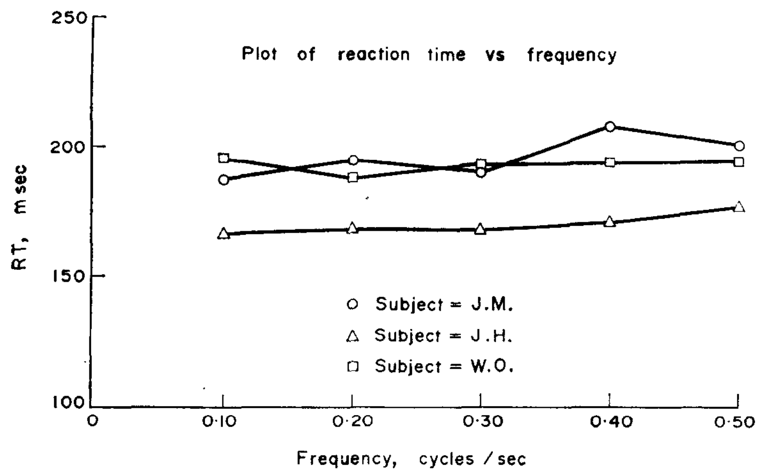


FIG. 4. Plot of RT vs. Frequency. Each point represents the mean RT at the corresponding frequency regardless of phase. Note that there is a slight increase in RT with increasing frequency.

TABLE 1. COMPARISON OF RESULTS FOR HORIZONTAL–VERTICAL AND HORIZONTAL–HORIZONTAL EXPERIMENTS (all values in msec)

Freq. (Hz)	RT (H–V)	RT (H–H)
Subject: J.H.		
0·1	166	169
0·3	168	164
0·5	178	166
Subject: W.O.		
0·1	195	194
0·3	193	190
0·5	195	192

It can be seen from Table 1 that there is no significant difference between the case when both the saccadic and smooth pursuit responses are in the same plane or in orthogonal planes.

DISCUSSION

The results obtained in this experiment are almost identical for all five values of target frequency. There seems to be no evidence that RT is a function of phase. Figure 4 does indicate that there is a slight increase in RT as target velocity is incresed. These facts indicate that for the range of target velocities covered in this experiment, the combined systems performance is independent of target position; it is, however, a function of target frequency (the *t* statistic gives a 98 per cent confidence interval). Since we know that the smooth pursuit system's performance is limited by target velocity (RASHBASS, 1961; ROBINSON, 1965), it is not unwarranted to assume that in this experiment, the velocity dependence can be attributed to the vertical smooth pursuit system. Thus, the results indicate that the horizontal saccadic and vertical smooth pursuit systems are parallel processors, the vertical smooth pursuit system being performance limited by target velocity.

The conclusions regarding the relationship of the horizontal smooth pursuit and saccadic systems based upon the results in Table 1 are that they are independent and this is in agreement with the findings of RASHBASS (1961). As reported in another paper (FEINSTEIN and WILLIAMS, 1971) the horizontal and vertical saccadic systems are complexly interrelated. In summary, the experimental findings to date indicate the following relationships:

1. The horizontal smooth pursuit and saccadic systems are independent.
2. The horizontal and vertical saccadic systems are complexly interrelated.
3. The horizontal saccadic and vertical smooth pursuit systems are independent.

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Abstract—The human oculomotor system has been studied by numerous people for well over half a century. Since the visual system is our primary sensory input channel, it is important for us to know how information is processed by the system. Most of the previous work on eye movements has been on modeling the horizontal eye movement control system.

In the present series of experiments, human subjects were given the task of tracking a spot of light which moved both horizontally and vertically. The temporal relationship of the horizontal and vertical eye movements was recorded using a light reflection technique. The results of this experiment indicate that the horizontal saccadic and vertical smooth pursuit systems are parallel information processors and are not interdependent.

Résumé—De nombreuses études ont été consacrées au système oculomoteur humain depuis bien plus d'un demi siècle. Comme le système visuel est notre principale source d'information sensorielle, il nous importe de connaitre le traitement de l'information dans ce système. La plupart des travaux antérieurs sur les mouvements des yeux ont recherché un modèle du système de contrôle du mouvement horizontal de l'oeil.

Dans la série présente d'expériences les sujets humains devaient suivre un point lumineux qui se déplaçait à la fois horizontalement et verticalement. On enregistrait par une technique de réflexion de lumière la relation temporelle des mouvements des yeux horizontaux et verticaux. Il en résulte que les saccades horizontales et la poursuite verticale régulière sont des systèmes parallèles de traitement de l'information et ne sont pas interdèpendants.

Zusammenfassung—Das okulomotorische System des Menschen wurde an zahlreichen Personen über gut ein halbes Jahrhundert untersucht. Da das visuelle System der Anfang unseres sensorischen Kanals ist, ist es für uns wichtig zu wissen, wie Information vom System übertragen wird. Die meisten der früheren Arbeiten über Augenbewegungen überprüften die Horizontalbewegungen des Auges.

In den vorliegenden Experimenten hatten die Versuchspersonen die Aufgabe, horizontal und vertikal bewegten Lichtpunkten zu folgen. Über Reflexionsmessungen wurde die zeitliche Abhängigkeit der horizontalen und vertikalen Augenbewegungen aufgezeichnet. Es ergab sich, daB die horizontalen Sakkaden und die vertikalen langsamen Bewegungen gleichzeitig Information liefern, die nicht voneinander abhängig ist.

Резюме — Окуломоторная система человека изучалась многими исследователями в течение более чем полстолетия. Поскольку зрительная система является нашим основным сенсорным входным каналом, для нас важно знать как передается информация этой системой. Большинство предшествующих работ моделировали контрольную систему горизонтального движения глаза.

Результаты этих экспериментов, в которых испытуемым-людям была предложена задача следить за световым пятном, которое движется как в горизонтальном, так и в вертикальном направлениях, показывают, что горизонтальная саккадическая и вертикальная плавно-прослеживающая системы являются параллельно функционирующими системами информации, но не зависящими друг от друга.