Target-Directed Head Movements in a Head-Coupled Virtual Environment: Predicting the Effects of Lags Using Fitts' Law

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Two experiments have investigated the effects of lag on discrete target-directed head movements in a virtual environment. Both the target and a head-slaved pointer (subjected to lag) were presented on a head-mounted display. Target-directed head movements in the presence of a constant time lag were shown to obey Fitts' law ($R^2 > .93$). A previously reported interaction between the effects of lag and the effects of index-of-difficulty on hand movement time could not be found in head movement time when the target width was kept constant. Further experiments suggested that there is a significant interaction between the effects of target width and lag but not between target distance and lag. A model predicting head movement strategy in the presence of lag is proposed to explain the experimental findings. This model predicts, and experiments verified, that for a target width from 1° to 8° and a target distance range of 2.5° to 30°, the effect of lag (up to 267 ms) on target-directed head movement is independent of target distance but dependent on target width. Actual or potential applications of this research include the design of virtual control panel and its layout in a Virtual Reality simulator.

INTRODUCTION

Background

A head-coupled virtual environment is a space-stabilized computer-generated scene presented through a head-mounted display (HMD). Users can view appropriate portions of the scene according to their head positions, which are measured by a head tracking system (Figure 1). A combined HMD, head tracking system, and graphics host computer can be used to generate an immersive virtual environment, which has also been referred to as a head-coupled virtual reality system (So & Griffin, 1995b).

Head tracking systems allow the development of head-controlled pointing devices. For example, the ability to search and locate targets with a head-slaved radar probe can benefit a pilot in an air-to-air combat situation (Barnes, 1989). Also, a head-slaved sensing probe can be useful in telerobotics operations (Barfield & Furness, 1995; Kalawsky, 1993). With increasing use of head-coupled virtual reality simulation and prototyping systems, head controlled tasks will also increase (e.g., driving simulation; Bayarri, Fernandez, & Perz, 1996). In spite of the benefits of head-control systems, there are problems associated with the response dynamics. In head-slaved devices controlled by target-directed head movements, inevitably there will be a lag between the moment the head moves and the moment the head-slaved device follows.

For training purposes, the task of controlling a slowly responding head-slaved device can be simulated with a head-coupled virtual reality system. During the simulation, a pointer (or reticle) on the HMD can represent the position of the head-slaved device. As the head moves, the reticle follows with the response lag of the

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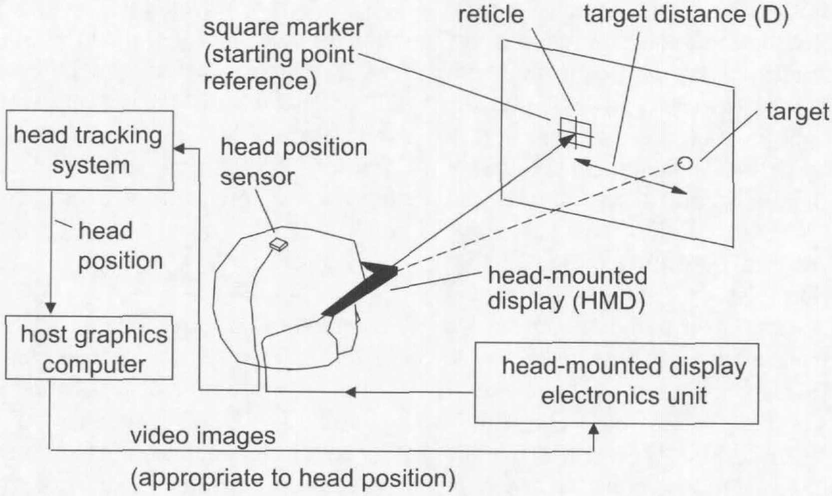

Figure 1. Illustration of the apparatus setup and the images presented on the experimental head-coupled virtual display system.

pointing device. This type of lag has been referred to as reticle lag (So & Griffin, 1993). Figure 2 illustrates the effect of reticle lag on the position of a head-slaved reticle presented on a head-coupled virtual display during head movements. A previous experiment showed that reticle lags of 67 ms or more can significantly degrade continuous tracking performance with a head-slaved reticle (So & Griffin, 1995a). In a typical target search-and-acquisition task, head movements are more likely to be discrete than continuous. Therefore there is a need to understand effects of reticle lags on discrete target-directed head movements.

Fitts' law has been widely used to predict movement times between a starting point and a finishing point in the presence of lags (Fitts & Peterson, 1964). There have been numerous studies of Fitts' law with a head-slaved physical pointer and a physical target, and head movement times have been found to agree with the predictions of Fitts' law (e.g., Andres & Hartung, 1989; Jagacinski & Monk, 1985). Effects of control gain (Lin, Radwin, & Vanderheiden, 1992) and target distance, size, and direction (Radwin, Vanderheiden, & Lin, 1990) have also been reported. However, these studies used either physical targets or targets presented

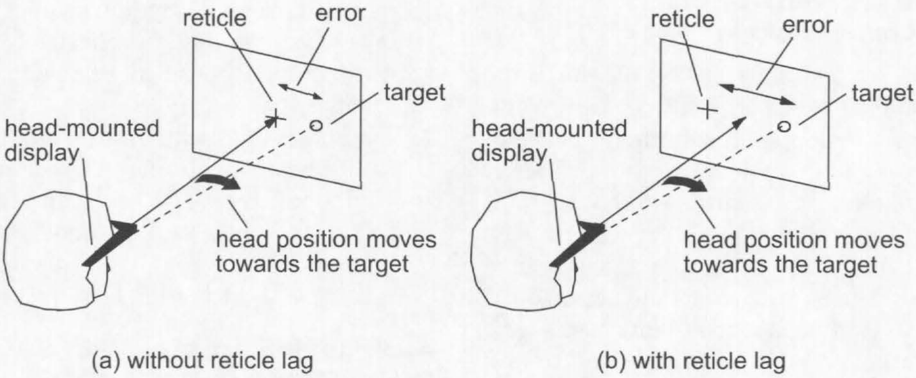

Figure 2. Presentation of a head-slaved reticle on a head-coupled virtual display, with and without reticle lag.

on a panel-mounted display. Similar studies with a projected head-slaved pointer in a virtual environment have not been reported. Eggleston and Janson (1997) investigated the effects of field-of-view on a Fitts' tapping task presented in a virtual environment. However, the task was manually controlled and not head controlled.

A review of the literature indicates that studies using Fitts' law to predict the effects of lag have concentrated on manually controlled tasks and not on head-controlled tasks. These manually controlled tasks included the use of master-slave control devices (e.g., Hill, 1976; Hoffmann, 1992; Sheridan & Ferrell, 1963; and Starr, 1979) and a mouse-controlled cursor presented on a panel-mounted display (e.g., MacKenzie & Ware, 1993). Rogers, Spiker, and Fischer (1997) reported on the effects of lag on a discrete head-controlled task. Results showed that task performance decreased monotonically with increasing lag. Fitts' law was not used in their studies, and targets were displayed on a panel-mounted monitor.

This paper (a) reviews a model proposed by Hoffmann (1992) to predict the effects of lag on discrete manually controlled tasks; (b) reports a preliminary study suggesting that Hoffmann's model on manually controlled tasks is not adequate for predicting the effects of lag on discrete head-controlled tasks; (c) proposes an improved model for the effects of lags on discrete head-controlled tasks; and (d) reports an experiment conducted to verify the newly proposed model.

Effects of Lag with Discrete Manual Control Tasks

Hill (1976) and Starr (1979) measured the discrete aiming task performance with manually controlled robotic arms in the presence of lags. They found that with lags of up to 3 s, the time to complete the task increased linearly with increasing lag. Hoffmann (1992) used Fitts' law to predict the effects of lags on target-directed movement times with manually controlled pointers. In Hoffmann's study, participants were asked to rotate a knob to move a pen from a starting point to a finishing point. The pen followed the knob movement with four time lags: 30 ms, 200 ms, 500 ms, and 1000 ms. Results showed that movement times increased with increasing lag and that the increases were found to be proportional to the index of difficulty (ID). That is, the greater the ID, the greater the effects of lag. Hoffmann proposed a modification of Fitts' law to predict the effects of lag on a manually controlled pointer's movement time (MT):

$$MT = a + b\,(c + lag)\log_2(2D/W) \qquad (1)$$

in which a, b, c are constants, D is the target distance, W is the target diameter (width), lag is the response time delay of the manual pointer, and $\log_2(2D/W)$ is the index of difficulty. In his paper Hoffmann reported that his model is consistent with the results of two previous studies concerning effects of lag on discrete, manually controlled tasks (Ferrell, 1965; Sheridan & Ferrell, 1963).

Similar findings regarding movement time, index of difficulty, and lag were also reported by MacKenzie and Ware (1993) in a study concerning target-directed cursor movements. Targets were presented on a workstation monitor (i.e., a panel-mounted display) and subjects were asked to move a mouse-controlled cursor toward the targets. The results from Hoffmann (1992) and MacKenzie and Ware suggest that the increase in movement time due to lag depends on the ID. That is the higher the ID, the larger the effects of lag. When applying Hoffmann's model to discrete head-controlled tasks in a virtual environment, the following predictions concerning head movement times can be made:

1. There will be significant interactions between the effects of lag and the effects of the index of difficulty on head movement times (see Equation 1).
2. Regression lines fitting Fitts' law to movement times with constant lag will meet at a single point (the y intercept, a, when $\log_2(2D/W) = 0$; see Equation 1) and their gradients (b (c + *lag*); see Equation 1) will increase with increasing lags.

Applying Hoffman's Model to Head Movement

A preliminary study was conducted to investigate the effects of lag on target-directed head movements. In that experiment, 12 male participants, five indices of difficulty (one target size: 1.2° in diameter and five target distances: 2.5° to 10° in length), and six repetitions were used. Targets were presented on a 17° × 17° HMD, and participants were asked to acquire the target with a head-slaved reticle subjected to three reticle lags (0, 67, and 133 ms). A graphical illustration of the target and the head-slaved reticle is included in Figure 2. The target size of 1.2° was arbitrarily chosen to fit the field-of-view of the HMD and represented an icon 10 mm in diameter viewed at a distance of 500 mm. The 10 mm refers to the typical dimension of a keypad on a PC keyboard and the 500 mm is about halfway between the maximum hand reach envelope (620 mm) and the minimum hand reach envelope (397 mm) of a 50th percentile male Chinese adult (Pheasant, 1986).

Data from the first test run were excluded from the data analysis to eliminate the effects of practice. The effects of repetition were significant before the exclusion: analysis of variance (ANOVA) $F(5, 1060) = 6.4$, $p < .0001$, and not significant after the exclusion, $F(4, 881) = 0.16$, $p = .34$. ANOVA results indicated that movement times increased with both index of difficulty, $F(4, 881) = 74.3$, $p < .0001$, and lag $F(2,881) = 74.2$, $p < .0001$. The ANOVA table for the movement time measurements (excluding the first repetition) is shown in Table 1. Fitts' law regression lines were fitted to the movement times (*MT*) obtained with the three lags:

$$\text{lag} = 0\text{ ms} \quad MT(\text{s}) = -0.320 + 0.283\ (ID) \quad R^2 = .98$$
$$\text{lag} = 67\text{ ms} \quad MT(\text{s}) = -0.216 + 0.315\ (ID) \quad R^2 = .94$$
$$\text{lag} = 133\text{ ms} \quad MT(\text{s}) = -0.044 + 0.306\ (ID) \quad R^2 = .93. \qquad (2)$$

These regression lines are illustrated in Figure 3. Inspection of Figure 3 indicates that the three lines do not meet at a single point. In fact they are approximately parallel to each other, which suggests that there is no interaction between the effects of lag and the effects of ID on movement times. The ANOVA confirms that there was no significant interaction between lag effects and ID effects $F(8, 881) = 0.67$, $p > .7$. This contradicts the prediction of Hoffmann's (1992) model. A multiple regression analysis was performed on the movement time data:

$$MT(\text{s}) = -0.081 + 0.21\ (ID) + 0.0023\ (lag) + 0.00007\ (ID \times lag);\ R^2 = .7 \qquad (3)$$

The probability values for the various terms are as follows:

Constant	$p < .02$
Lag	$p < .001$
ID	$p < .001$
ID × *Lag*	$p > .56$

From the analysis, it can be seen that the term (*ID* × *Lag*) did not make a significant contribution to the movement time (*MT*). This suggests that Hoffmann's (1992) model, which predicts an interaction between ID and lag, was not applicable in this case. An obvious explanation for the difference between the findings by Hoffmann and this preliminary study is that the former investigated hand movement, while the latter investigated head movement. However, another possible explanation is that the interaction between MT and ID reported by Hoffmann was attributable to the interaction between lag and target size and not between lag and target distance: only target size was varied in Hoffmann's study and only target distance was varied in this preliminary experiment. In order to confirm this reasoning, another experiment investigating the effects of lag with different target sizes and distances was needed. A model explaining the sole dependency between lag effects and target size effects is reported in the next section.

A Model of the Effects of Lag on Target-Directed Head Movement

In Hoffmann's (1992) study, dependency between the effects of lag and the effects of ID was based on the assumption that participants used a move and wait strategy throughout the duration of the target-directed hand movement. In simple terms, Hoffmann's model suggests that a user will split the hand movement into *n* steps, and each step will consist of a discrete movement and a waiting period equivalent to the lag duration. The logic behind this strategy

TABLE 1: ANOVA Table of Movement Time Measurements (s) Collected in the Preliminary Experiment (Excluding Data from the First Repetition)

Source	*DF*	Sum of Squares	Mean Square	*F* Value	Pr > *F*
ID	4	42.28	10.57	74.31	0.0001
Lag	2	21.10	10.55	74.19	0.0001
Repetition	4	0.64	0.16	1.13	0.3397
Lag × ID	8	0.76	0.10	0.67	0.7224
Error	881	125.31	0.14		
Corrected total	899	190.10			

is that the participant would need to see the delayed effects of each step before proceeding to the next step of hand movement. With this move-and-wait strategy, the effect of the lag is proportional to the number of steps (n), which in turn is a function of both target distance (D) and target width (W). Hence there is an interaction between effects of lag and ID.

In our preliminary experiment, no evidence of this type of movement was found among recorded target-directed head movements in the presence of lag. Instead, target-directed head movements in the presence of lag were found to consist of two distinct stages: a smooth, continuous ballistic head movement from the starting point toward the target, followed by a series of move-and-wait movements. The difference between target-directed hand movement and head movement may be a result of the anatomical differences between the hand and the head. Unlike the hand, the head is a constrained body part with a high moment of inertia.

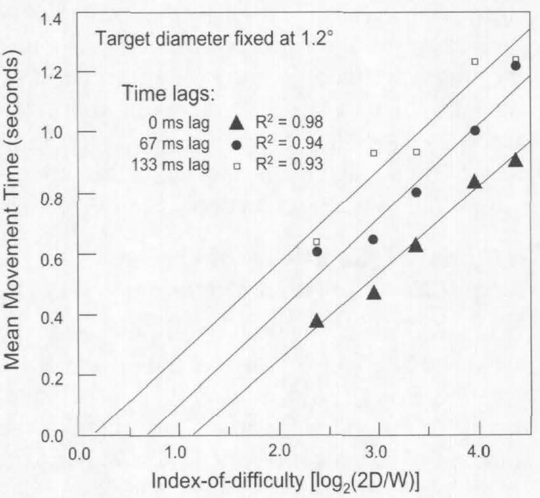

Figure 3. Head movement times with 3 reticle lags as a function of indices of difficulty (means from 12 participants and 5 repeated runs).

A typical target-directed head movement in the presence of lag is shown in Figure 4. Figure 5 illustrates the various stages of a modeled target-directed head movement. As shown in Figure 5, MT between the moment the head moves and the moment the reticle is resting on the target is the sum of three components: (a) time lag, L, (point A to B); (b) MT of the first ballistic movement from the starting point to the first stopping point near the target (point B to C); and (c) MT of a series of move-and-wait movements homing into the target (point C to D).

During the first ballistic movement toward the target, operators will not notice lag effects until they have started to move, by which time the ballistic movement has already been initiated. Therefore the first ballistic MT should be independent of lag. If there is no lag, this ballistic movement is enough to move the aiming reticle from the starting point to the target. However, because of the lag, the reticle will miss the target and participants will be forced to make a series of move-and-wait adjustments to compensate for the extra deviation (see Figure 4) resulting from the lag. In other words the time taken by the first ballistic movement is approximately equal to MT in the absence of lag ($MT_{lag=0}$). As explained in Hoffmann (1992), each move-and-wait movement has a duration equal to the sum of time lag (L), reaction time (RT), decision time (DT), and MT (t_m). It is assumed that t_m can be absorbed into lag (L) and that RT and DT are constants represented by t_{rd}. Time taken by n move-and-wait movements is therefore [n ×

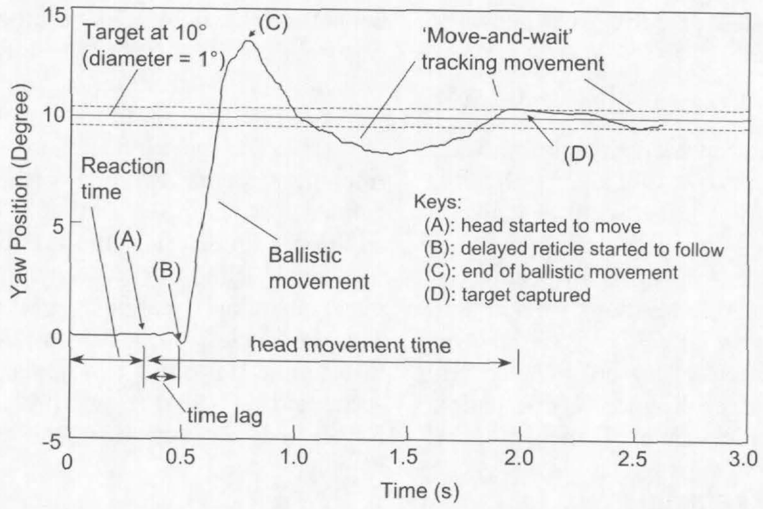

Figure 4. A typical time history trace of a target-directed head-slaved reticle movement in the presence of lag (data from one participant with target distance = 10°, target width = 1°, and lag = 133 ms).

$(L + t_{rd})$], and MT of the whole target-directed head movement is

$$MT = \underset{\text{(lag)}}{L} + \underset{\text{(ballistic movement)}}{MT_{lag=0}} + \underset{\text{(move-and-wait movements)}}{[n \times (L + t_{rd})]}. \quad (4)$$

In order to move the reticle toward the target, the amplitudes of each successive move-and-wait movement must be reduced. It is assumed that the rate of reduction in amplitude is $p\%$, where p is less than 100. When the reticle can finally rest on the target, the number (n) of move-and-wait movements satisfies the following condition:

Initial deviation

$$(d) \times (p\%)^n = \text{target width } (W)/2$$
$$d \times (p\%)^n = W/2$$
$$(p\%)^n = W/2d \quad (5)$$

By simplifying Equation 5 and substituting it

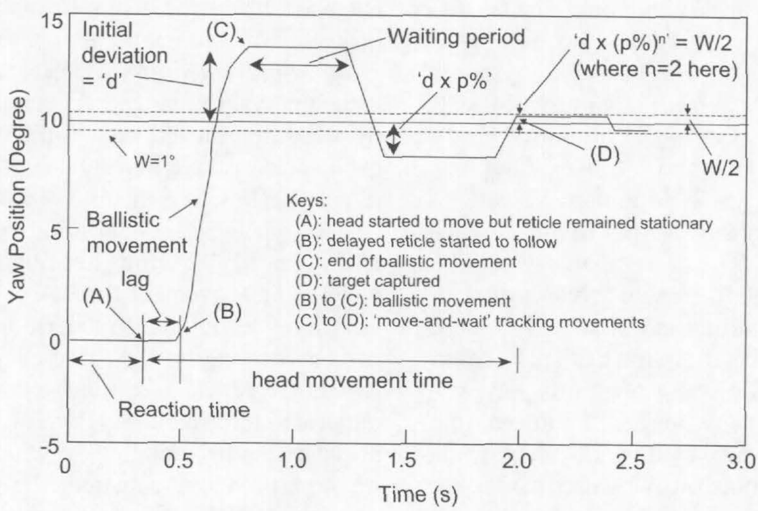

Figure 5. A proposed model of target-directed, head-slaved reticle movements in the presence of lag with ballistic and move-and-wait movements.

into Equation 4 (see Appendix), the following equation is obtained:

$$MT = A + B(ID) + C(L) + E(L)\log_2(2/W) \quad (6)$$

in which MT is head movement time; A, B, C, and E are constants; ID is index of difficulty; L is time lag; and W is target width. Details of the derivation from Equation 5 to Equation 6 are included in the Appendix. Inspection of Equation 6 indicates that although the effects of lag (L) and target width (W) on MT have an interaction, the effects of lag are independent of the effects of target distance (D). Equation 6 will be tested in the main experiment.

EXPERIMENT

Objectives and Hypotheses

The objectives of the main experiment are to investigate the use of Fitts' law to predict the effects of reticle lag and to verify the relationship among target distance, target width, time lag, and head movement time. It is hypothesized that

1. as the reticle lag increases, the MT will increase.
2. the increases in MT caused by lag will increase with decreasing target size.
3. the increases in MT caused by lag will be independent of changes in target distance.

Apparatus

The experimental head-coupled virtual display system consisted of a VR4 Biocular head-mounted display (Virtual Research Systems, Inc., Santa Clara, CA), a Polhemus 3-SPACE head tracking system (Polhemus Inc., Colchester, Vermont), and a Silicon Graphics Onyx workstation (SGI, Mountain View, CA) (Figure 1). Images on the display were focused at about 5 m. Participants wore the display in front of their eyes while seated in darkened surroundings so that only visual stimuli from the head-mounted display could be seen. The field-of-view of the display was 50° (horizontal) × 33° (vertical), and the total weight of the display was 0.94 kg. Weight was balanced and a chinstrap was used to secure the display. Wells and Griffin (1987) reported that when tracking a slow-moving target (at frequencies below 1 Hz), increases in balanced helmet weight up to 3.3 kg did not significantly affect head tracking performance. The Polhemus 3-SPACE head tracking system sampled head position 60 times/s with a resolution of 0.08°. The measurement noise of the head tracking system, recorded with a stationary helmet, was about 0.1° r.m.s. in both axes. In addition to reticle lag, the duration of which was manipulated in this study, the virtual display system had a baseline lag of about 25 ms. This lag included a 16.7–ms delay used to measure head position and update the graphics scene and a 0– to 16.7–ms presentation delay for an image to appear on the head-mounted display.

Measurements

The dependent variables measured in both experiments were head RT and head MT.

Head reaction time. Head reaction time is the interval measured between the onset of a stimulus and initiation of the head movement response (Boff & Lincoln, 1988). In this study the moment at which a head response was initiated was referred to as t_i, with t_i being the first moment at which the following condition was satisfied: For times greater than and equal to t_i, either the yaw axis or the pitch axis displacement of the head-slaved reticle from the center of the starting point (i.e., the square marker position in Figure 1) was greater than 0.5°. In the presence of an imposed reticle lag, lag was subtracted from t_i so that measured head RT was not contaminated directly by lag.

Head movement time. Head movement time is the interval measured between the time when the head first moved (t_i) and the time when the head-slaved reticle first made contact with the target (t_c) (Boff & Lincoln, 1988). In the presence of reticle lag, similar to other studies (e.g., Hoffmann, 1992), the duration of the lag is included in movement time. A target-capturing criterion was defined to determine when a reticle was resting on the target. The moment at which the reticle first made contact with the target was referred to as t_c, with t_c being 350 ms ahead of the first moment at which the following condition was satisfied: the center of the reticle was inside the target circle (see Figure 1) for 350 ms, of which no more than 67 ms was spent momentarily outside the target circle. This criterion was adapted from Jagacinski and Monk (1985). Both yaw and pitch axis measurements were considered.

This study was approved by the Committee on Research Practice at the Hong Kong University of Science and Technology. All participants were given written instructions about the purpose and methods of the experiments. Their written consent was obtained before the experiments.

METHOD & DESIGN

A total of twelve male university students and staff participated in the experiment. They performed a series of target acquisition runs with a head-slaved reticle. Participants of the same gender were used to eliminate effects of gender variable. Because only male participants were used in Hoffmann's (1992) studies, it was decided only male participants would be used in this experiment as well. Both the reticle and the target were presented on the experimental head-mounted display: The reticle was a 6° × 6° cross, and the target was a circle with a diameter determined by the target size condition. Each run lasted about 15 s. At the start of each run, participants were asked to keep the reticle on top of a square marker shown on the display for 2 s (Figure 1). Then appeared a target, but participants were asked to continue to keep the reticle on the square marker. This ensured that all participants perceived the target size and distance before making a movement.

When the reticle had been on the square marker for 2 s after the appearance of the target, the square marker disappeared. This indicated the onset of the stimulus. Participants moved the head-slaved reticle toward the target as quickly as possible and kept it on top of the target. When the reticle was on top of the target for 0.35 s, the target was captured, although data collection processes went on for another 0.25 s. This was done to test the effects of different capturing criteria at a later stage (see the "Results and Discussion" sections of the main experiment).

Written instructions were given to participants before the experiment, and each individual was given 9 practice runs followed by 6 repetitions of 36 runs. The 36 runs exhausted the combinations of three target distances (10°, 20°, and 30°), four target diameters (1°, 2°, 4°, and 8°), and three reticle lags (0, 133, and 267 ms corresponding to 0, 8, and 16 frame delays). Within each repetition, the presentation order of the 36 combinations was randomized, and there was a 2-min rest between each repetition session. The target was presented along the yaw axis plane of the square marker, as shown in Figure 1. Only one target direction was used. Jagacinski and Monk (1985) reported that target-directed head movements obey Fitts' law regardless of target direction. Radwin et al. (1990) have also investigated the effects of target direction on head movement times.

RESULTS

An ANOVA was performed to determine the effects of repeated results. This analysis indicated that head MT was significantly affected by repeated runs $F(5, 2567) = 29$, $p < .0001$. When data from the first and the last two repeated runs were excluded from the analysis, the effects of repeated runs were not significant, $F(2, 1274) = 2.2$, $p > .1$). A possible reason is that participants were still in the learning stage during the first run and were fatigued during the last two repetitions: A typical experimental session lasted about 80 m. The exclusion was based on the grouping result of a Student-Newman-Keuls (SNK) multivariable comparison analysis. In order to minimize the effects of learning, data from the first and last two repeated runs were excluded in all subsequent data analyses. Head reaction times were measured, and ANOVA tests indicated that they were unaffected by lag, $F(2, 1274) = 1.12$, $p > .3$, target size $F(3, 1274) = 0.53$, $p > .6$, and target distance, $F(2, 1274) = 0.61$, $p > .5$. This is consistent with the prediction by Fitts and Posner (1967) that for a target-directed movement, reaction time is not related to either target distance or target size. The ANOVA table for the reaction time measurement is included as Table 2.

Target-directed head movement times with different lags are shown in Figure 6 as functions of ID. Movement times with a constant target distance are illustrated in Figure 6a

TABLE 2: ANOVA Table of Reaction Time Measurements Collected in the Main Experiment (Excluding Data from the First and Last Two Repetitions)

Source	DF	Sum of Squares	Mean Square	*F* Value	Pr > *F*
Lag	2	0.011	0.005	1.12	0.3250
Width	3	0.008	0.003	0.53	0.6633
Distance	2	0.006	0.003	0.61	0.5459
Replication	2	0.022	0.011	2.21	0.1103
Lag × Distance	4	0.013	0.003	0.65	0.6281
Lag × Width	6	0.032	0.005	1.07	0.3756
Error	1274	6.236	0.005		
Corrected total	1293	6.326			

(i.e., variations of ID depend solely on changes in target size), and Figure 6b illustrates the MT data with a constant target size. Mean data of 12 participants over the remaining three repeated runs are used in the plots. Inspection of Figure 6a shows that as lag increased, MT increased and increases in MT caused by lag increased with decreasing target size (i.e., increasing ID). The shape of these regression lines is characterized by a common intersection point and increasing gradients with increasing lag. This is similar to the data reported by Hoffmann (1992).

Inspection of Figure 6b indicates that increases in MT caused by lag remained constant with changes in target distance. The shape of these regression lines is characterized by parallel lines, a finding similar to the data obtained in the preliminary experiment. Results of an ANOVA indicated the following: (a) head MT as significantly affected by lag, $F(2, 1274) = 271$, $p < .0001$, target distance, $F(2, 1274) = 96.6$, $p < .0001$, and

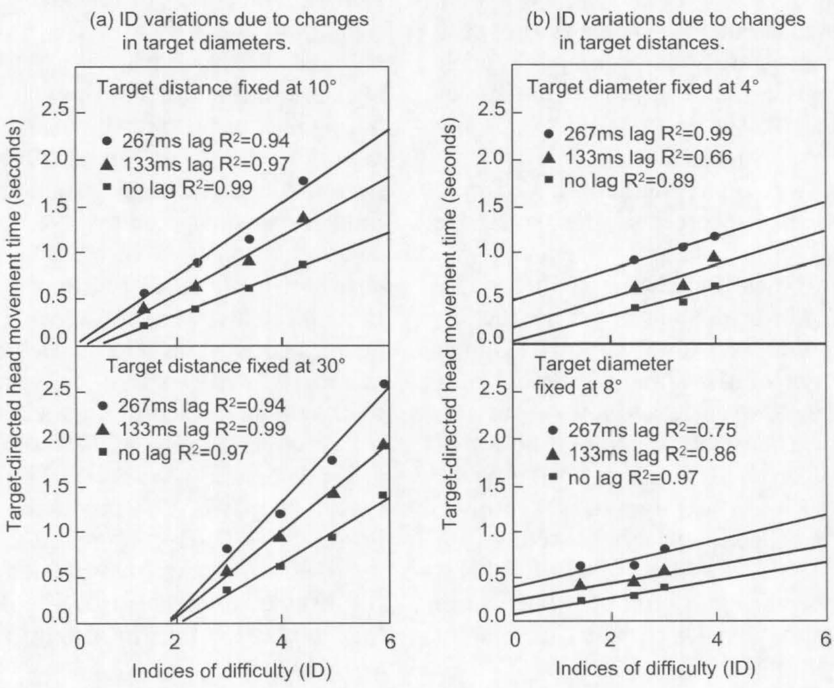

Figure 6. Mean head movement times with different lags as functions of indices of difficulty: (a) target distance was kept constant, (b) target size was kept constant (data from 12 participants, mean of three repeated runs).

TABLE 3: ANOVA Table of Movement Time Measurements Collected in the Main Experiment (Excluding Data from the First and Last Two Repetitions)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Lag	2	101.37	50.68	270.93	0.0001
Width	3	253.46	84.49	451.62	0.0001
Distance	2	36.13	18.06	96.56	0.0001
Replication	2	0.83	0.41	2.21	0.1103
Lag × Distance	4	1.47	0.37	1.96	0.0985
Lag × Width	6	14.98	2.50	13.34	0.0001
Error	1274	238.33	0.19		
Corrected total	1293	646.56			

target size, $F(3, 1274) = 452$, $p < .0001$; (b) there were significant interactions between lag effects and target size effects, $F(6, 1274) = 13.3$, $p < .0001$; and (c) there was no significant interaction between effects of lag and effects of target distance, $F(4, 1274) = 1.96$, $p = .1$.

The ANOVA table for MT measurements (excluding the first and last two repeated runs) is shown in Table 3. These findings support the three hypotheses of this experiment: (a) as reticle lag increases, MT increases; (b) MT caused by lag increases with decreasing target size; and (c) increases in MT caused by lag are independent of changes in target distance.

A linear regression analysis was conducted to fit the MT data as a function of lag (L), index of difficulty (ID, $\log_2(2D/W)$), and the multiplicative combinations of L and D (target distance) as well as L and W (target width):

$$MT(\text{s}) = -0.283 + 0.2553\, ID - 0.000162\, L \times \log_2(D) + 0.000957\, L \times \log_2(2/W) + 0.002373\, L \qquad R^2 = .8 \qquad (7)$$

The significant levels indicating the contribution of each term to MT are as follows: constant, $p < .0001$, ID, $p < .0001$, $L \times \log_2(D)$; $p > .05$, $L \times \log_2(2/W)$, $p < .0001$, L, $p < .0001$. Inspection of the statistics confirms that the term $L \times \log_2(D)$ does not make a significant contribution to the MT and therefore should be removed from the regression equation. A further regression analysis was conducted, and the terms $\log_2(D)$ and $\log_2(2/W)$ were combined:

$$MT(\text{s}) = -0.3196 + 0.2652 \log_2(2D/W) + 0.000912\,(L) + 0.003027\, L \times \log_2(2/W) \qquad R^2 = .8$$

Equation 8 is similar to Equation 6, which is the proposed model.

In this study a target-capturing criterion requiring a time on target of 350 ms was used. In order to determine the effects of different time-on-target requirements, all the data analyses (including the ANOVA) were repeated with a time-on-target requirement of 500 ms. The results (including all the ANOVA results) were similar to those obtained with the 350-ms time-on-target criterion.

DISCUSSION

The main contribution of this study is the validation of the independence of the effects of lag and target distance in target-directed head movement time. Results of two experiments indicated that whereas lag and target width have a multiplicative effect on movement time, the effects of lag were not influenced by target distance. This suggests that in the presence of a lag, doubling the target distance would not have the same effect on movement time as would halving the target width.

With the widespread application of Fitts' law, use of the index of difficulty ($\log_2(2D/W)$) has become standard. Hoffmann (1992) studied the effects of lag on target-directed hand movement and reported that lag and ID have a multiplicative effect on hand movement time. He proposed the following equation:

$$MT = \text{A} + \text{B}\,(ID) + \text{C}\,(lag)\,(ID) \qquad (9)$$

In other words, for a given lag, doubling the target distance (D) would have the same effect on hand movement time as halving the target width (W). Such a relationship was not found in our preliminary experiment.

Based on measured target-directed head movement data, Hoffmann's model, which was developed to preuict the effects of lag on hand movement, was modified to predict the effects of lag on target-directed head movement. A further experiment was then conducted to study the relationships among head movement time, lag, target width, and target distance. Significant interactions were found between the effects of lag and target width but not between those of lag and target distance. Regression analysis suggested the following equation:

$$MT = A + B\,(ID) + C\,(lag) + E[lag \times \log_2(2/W)]. \qquad (10)$$

This regression result agreed with the proposed model. According to this model, in the presence of lag, doubling the target distance may not have the same effect on head movement time as halving the target width. This is important because it suggests that when investigating head movement time in a virtual environment with lag, the effects of target width and distance should be analyzed separately rather than simultaneously as index of difficulty. Note that a single movement direction was used throughout the study. Future research to study the implication of this finding in the presence of other influencing factors is desirable.

CONCLUSIONS

Without reticle lags, target-directed head movements were consistent with predictions of Fitts' law (i.e., head movement times were directly related to the index of difficulty, which is the logarithm of the ratio of target distance to target diameter). With a discrete target acquisition task in the yaw axis, head movement times increased significantly with reticle lag of 133 ms or more. Increases in movement times caused by lag increased with decreasing target size but were independent of changes in target distance. This suggests that an increase in target distance will increase only the index of difficulty, whereas an increase in target size will increase both the index of difficulty and the effects of lag. We propose a modification of Fitts' law to include the effects of lag on target-directed head movement time.

It appears that in a head-coupled virtual display system without lag, Fitts' law can be used to predict discrete target-directed head movement times. In a system with lag, movement times increase with increasing lag. These increases are independent of target distance but will increase with a reduction in target size. This result has important implications for the design of virtual control panels in virtual reality simulators with lag. In virtual reality systems in which lag is the major factor affecting performance, the accessibility of a virtual panel switch will depend more on its size than its location.

Current studies to extend this finding to manually controlled movements and other types of lag (e.g., image update lags) are continuing. The aim is to model and predict the effects of lag on visual-motor task performance in virtual environments.

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APPENDIX

The Derivation of Equation 6 as the Proposed Model of the Effects of Lag on Target-Directed Head Movement is as follows:

Equation 5 as explained in the main text:

$$(p\%)^n = W/2d. \qquad (5)$$

Taking logarithm to the base of 2:

$$n \times \log_2(p\%) = \log_2 (W/2d)$$

$$n = [\log_2 (W/2) - \log_2 (d)] / \log_2(p\%).$$

$2/W$ is used instead because it is closer to the target width component in the ID:

$$n = [\log_2 (2/W) + \log_2 (d)] / \log_2(1/p\%).$$

It is assumed that the initial deviation (d) will be proportional to the lag (i.e., d = X lag, where X is a constant) and $1/\log_2(1/p\%)$ can be represented by a constant, Y:

$$n = [\log_2(2/W) + \log_2(X\ lag)]\ Y$$
$$n = Y \log_2(2/W) + Y \log_2(X\ L), \quad (11)$$

where X and Y are constants, L is the lag, and W is the target width.

Substituting equation (11) into equation (4):

$$MT = L + MT_{lag=0} + [n \times (L + t_{rd})]$$

$$MT = L + MT_{lag=0} + \{[Y \log_2(2/W) + Y \log_2(X\ L)] \times (L + t_{rd})]\}$$

$$MT = L + MT_{lag=0} + Y(L) \log_2(2/W) + Y(L)\log_2(X\ L) + Y\ t_{rd} \log_2(2/W) + Y\ t_{rd} \log_2(X\ L).$$

Replacing Y t_{rd} with a constant Z:

$$MT = L + MT_{lag=0} + Y(L) \log_2(2/W) + Y(L)\log_2(X) + Y(L)\log_2(L) + Z \log_2(2/W) + Z \log_2(L) + Z \log_2(X).$$

Substituting the $MT_{lag=0}$ with Fitts' law equation (i.e., $MT_{lag=0} = A + B\ (ID)$):

$$MT = L + A + B(\log_2(2D/W)) + Y(L) \log_2(2/W) + Y(L)\log_2(X) + Y(L)\log_2(L) + Z \log_2(2/W) + Z \log_2(L) + Z \log_2(X).$$

Grouping and simplifying the following terms by absorbing the following constants using A, B, C, and E (Note: D is the target distance and not a constant):

Constant term: $A + Z \log_2(X) = A$

Terms with $\log_2(D)$: $B \log_2(D)$

Terms with $\log_2(2/W)$:
$(B + Z) \log_2(2/W) = C \log_2(2/W)$

Terms with (L) and $(L)\log_2(L)$:
$[1 + Y \log_2(X)]\ (L) + Z \log_2(L) + Y(L)\log_2(L) = E\ (L)$

Terms with $(L) \log_2(2/W)$:
$Y(L) \log_2(2/W) = F(L) \log_2(2/W)$

leads to:

$$MT = A + B \log_2(D) + C \log_2(2/W) + E(L) + F(L)\log_2(2/W).$$

Combining the terms $\log_2(D)$ and $\log_2(2/W)$ to $\log_2(2D/W)$ and reassigning the constants:

$$MT = A + B \log_2(2D/W) + C(L) + E(L)\log_2(2/W)$$

$$MT = A + B(ID) + C(L) + E(L)\log_2(2/W). \quad (6)$$

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