EFFECTS OF HAND MOVEMENT LAG ON DISCRETE MANUAL CONTROL TASKS IN VIRTUAL ENVIRONEMENTS

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Most Virtual Reality applications involve manual manipulation and suffer from lags. Effects of lag in a virtual environment have received much attention. However, effects of target distance and width had not been analyzed in separation. A study has been conducted to investigate the effects of, and interactions among, hand movement related lag, target distance, and target width on manual task performance in a virtual environment. With a constant hand-related lag, hand Movement Time obeys Fitts' law (R^2>0.85). Lags of 110 ms or above can significantly increase hand Movement Times and their effects have significant interactions with the effects of target width but not with target distance. This finding indicates that, in the presence of lag, the effects of target distance and width should be analyzed in separation.

INTRODUCTION

A Virtual Reality system provides a user friendly and interactive environment in which a user can see and manipulate computer-generated objects in real-time. When a user moves his / her hand, the hand's position and orientation are measured and used to render and update images on a Virtual Reality (VR) display. Virtual Reality systems are useful for vehicle simulation training (Kuhl *et al*., 1995), machine operation training (Lin *et al*., 1996), and digital prototyping (Bullinger and Fischer, 1998).

Because of the inevitable lags in sensing position and rendering graphics, a VR system can only respond to a user's hand movement after a certain time lag. This lag is referred to as the 'hand-related lag'. It is defined as the time between the moment at which the hand first moves and the moment at which the most updated hand image is displayed. Bryson and Fisher (1990) and Taylor *et al*. (1996) investigated the effects of lags in a virtual environment, they defines time lag as the time between the moment when a tracker or a user first moves and the time at which the most updated image is displayed on a Head Mounted Display (HMD). Jacoby *et al*., (1996) also reported a comprehensive study on the occurrence of lags within a VR system. The specific definition of hand-related lag separates it from the time lag associated with head movement. The latter has been the subject of many studies (e.g., with discrete tracking task: So and Griffin, 1995c; So *et al*., 1999; with continuous tracking task: So and Griffin, 1992, 1995a,b and 1996).

Kazak *et al.* (1993) and Kenyon and Afenya (1995) investigated the 'transfer of training' of a 'pick-and-place' task from a virtual environment to a 'real' environment. Both studies reported that lags increased the task completion times. A 150 ms hand-related lag was reported by Kenyon and Afenya (1995). Task completion times in a virtual environment were reported to be about ten times and two times greater than those in a 'real' environment (Kozak *et al.*, 1993; and Kenyon and Afenya, 1995, respectively). Although the degrading effects of lags have been reported, neither of the above studies investigated the mechanisms by which lag affected the task performance. Kenyon and Afenyon (1995) further stated that time lag in a virtual environment is one of the most dominated factors that could degrade the task performance. Ellis *et al.* (1997) conducted a study on the effects of hand-related lag on a continuous manual-tracking task in a virtual environment. They reported that the latency associated with rendering could increase the tracking error. In 1996, Kawara and his colleagues reported that hand-related lag do not significantly increase levels of visual fatigue when subjects were performing 'pick-and-place' tasks in a virtual environment (Kawara *et al*, 1996). Their explanation was that hand movement is normally executed by feed-forward control without visual feedback signals. During some preliminary trials, the authors of this paper observed that this was not the case with their subjects. Task performance in the presence of lags was not reported in Kawara *et al*. (1996).

Mackenzie and Ware (1994) studied the effects of mouse-related lag on discrete manual task performance. They used a Desktop Virtual Reality (VR) system (i.e., a VR system using a normal computer monitor as its display) and reported a significant degradation in performance by lag. In their study, the effect of mouse-related lag on hand Movement Time (MT) was modeled using a modified Fitt's Law. They found that the effect of lag was a multiple of the Index-of-Difficulties (ID) (i.e., MT = A+B*ID+C*(ID)*(Lag)). Their finding was consistent with Hoffman (1992)'s study on manual task in a real environment. However, a previous study by the authors has shown that the effects of head-related lag in a virtual environment is not a multiple of the ID when the target width is kept constant (So *et al*, 1999). A study concerning the effects of hand-related lags on a Fitts' type discrete tracking task was conducted. The purpose of this study was to determine the effects of, and the interactions among, hand-related lag, target distance, and target width. A model of the effects of hand-related lag based on Fitts' law will also be developed.

METHOD

The objectives of this study were to (i) investigate the effect of hand-related lag on manual discrete tracking task in a virtual environment, and (ii) model the performance of discrete manual task in the presence of lag. The hypotheses were: (i) hand movement time will increase with increasing hand-related lag, (ii) with a constant lag, the relationship among movement time, target width, and target distance will obey Fitts' law, (iii) the effects of lag will have no significant interaction with the effects of target distance, and (iv) the effects of lag will have a significant interaction with the effects of target width. The latter two hypotheses were based on a recent study concerning the effects of lags associated with head movement in a virtual environment (So *et al*, 1999). The dependent variable was hand movement time. In this experiment, target width (2, 4 cm), target distance (14, 18, 24, 54, 62, 70 cm), imposed head-related lag (0, 110, 220 ms), and imposed hand-related lag (0, 110, 220 ms) were manipulated. Although head-related lag was manipulated, this paper only deals with the results in the absence of imposed head-related lag. That is, imposed head-related lag is 0 ms through out the analyses in this paper. It should be noted that all the imposed lags were in addition to an inherent system lag of about 63 ms. This lag consisted of a 55 ms frame delay and a 0 to 16 ms lag in the raster scan display system.

The position and orientation of the head and hand were measured by a Polhemus tracking system capable of updating at 120Hz. The posture of the hand was measured by a CyberGlove^{TM} and a Silicon Graphics Onyx2 workstation was used to update the graphics in a virtual environment created using the World-Tool-Kit^{TM} software. Both the Polhemus system and the CyberGlove^{TM} were synchronized with the World-Tool-Kit^{TM} software. Images were displayed on a VR4 liquid crystal Head-Mounted Display (HMD) (resolution: 742X230 color elements per eye; Field-Of-View: 48° horizontal × 36° vertical). Stereo images were presented according to the inter-pupillary distance of each subject. In this study, the subjects were asked to hit a target square as fast as possible using the index finger of the virtual hand. A target capturing criteria used in previous studies were adopted (Jagacinski and Monk, 1985; So *et al.*, 1999). The experiment had 9 conditions exhausting the 9 combinations of hand and head-related lags. Each condition had 12 runs exhausting the 12 combinations of target distances and target widths. The order of presenting the runs and conditions were randomized. Each condition was repeated 4 time. There was a one-minute rest between each condition. Twelve healthy male aged between 19 to 40 participated in this experiment. They were paid HK$70 as a compensation for their time.

RESULTS

Although the experiment had studied both the effects of lags associated with hand and head movement, this paper is focusing on the hand movement data in the absence of head movement related lag. An ANOVA was conducted on hand movement time data collected in the absence of head movement lag. A significant effect of replications was found ($F_{3,1543}$=22.61, p<0.0001). The mean hand movement times with the four replications are illustrated in Figure 1. As shown in the figure, the mean performance is improving during the first two replications and this improvement is flattening out during the third and fourth replications.

After the first two replications were excluded from the ANOVA analysis, the effect of replication was no longer significant ($F_{1,649}$=0.04, p<0.83). As a result, the data from the first and second replications were excluded in all of the subsequent analyses.

Following the traditional way to analyze the results as reported in Hoffmann (1992) and Mackenzie and Ware (1994), an ANOVA was conducted to investigate the effects of hand-related lag and Index-of-Difficulty (ID). Both the lag and the ID had a significant effect on hand Movement Time (MT) (lag: $F_{2,649}$=194.8, p<0.0001; ID: $F_{11,649}$=40.71, p<0.0001). However, no significant interactions between the effects of lag and the effects of ID was found ($F_{22,649}$=1.32, p>0.14). This suggests that the effect of lag is not a multiple of ID; a result in disagreement with that of Mackenzie and Ware (1994).

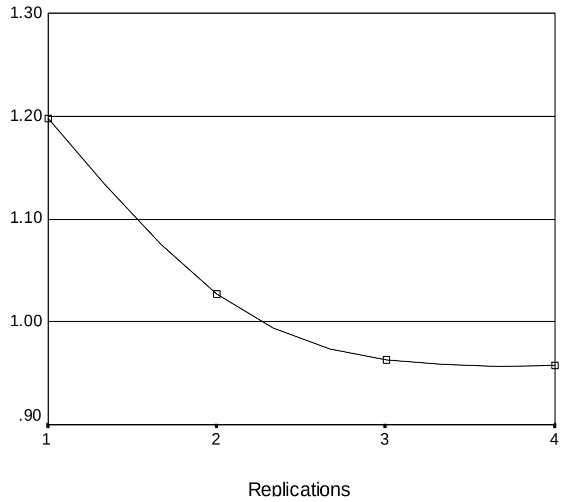

Figure 1. Target-directed discrete Hand Movement Times with four replications (means of all lag, target distance, and target width conditions).

A second ANOVA was performed investigating the effects of lag, target distance, and target width. In other words, the ID was separated into its components during the analysis. Not surprisingly, significant main effects were identified for hand-related lag ($F_{2,719}$=191.35, p<0.0001), target width ($F_{1,719}$=60.87, p<0.0001), and target distance ($F_{5,719}$=72.78, p<0.0001). Although no significant interaction was found between the effects of lag and the effects of target distance ($F_{10,719}$=0.93, *p*>0.5), a significant interaction between the effects of target width and the effects of lag was identified ($F_{2,719}$=6.19, p<0.005). This suggests that while the effects of lag is not a multiple of target distance, it is a multiple of target width or (target width)$^{-1}$ as explained in the Discussion Section.

DISCUSSION

With a constant lag, hand Movement Time (MT) increased linearly with the Index-of-Difficulty (ID) and the results of linear regression analyses indicate a R^2 greater than 0.85 (Figure 2). When hand-related lags of 110 ms or greater were imposed, the Movement Times increased significantly ($F_{2,719}$=191.35, p<0.0001). In 1994, MacKenzie and his colleagues modeled the hand Movement Time in the presence of mouse-related lag with a modified Fitts' law (MacKenzie and Ware, 1994). They found that the effect of lag has a significant interaction with ID and proposed to model the effects of lag as a multiple of lag (L) and ID. Their equation was:

$$MT = A + B*ID + C*Lag*ID \quad \text{Equation 1}$$

In this study, however, ID did not have a significant interaction with hand-related lag ($F_{22,649}$=1.32, *p*>0.14). Further analyses showed that significant interactions only exist between the effects of hand-related lag and target width, but not between the effects of hand-related lag and target distance (see Results Section). This finding suggests that the effects of lag only have a multiplicative effect with target width. The model proposed by MacKenzie and Ware (1994) is, therefore, not applicable to this study. A possible explanation for the differences between MacKenzie's findings and the results of this study is found after reviewing a study by Hoffmann in 1992. MacKenzie's model is very similar to that proposed by Hoffmann in 1992 which is based on the assumption of a 'move-and-wait' strategy by the subjects. In other words, when subjects move a hand controlled pointer from a starting point to a finishing point, they will divide the movement into a series of 'move-and-wait' steps so that the delayed action of each step is seen before they proceed to the next step. In the present study, such a 'move-and-wait' phenomenon could not be observed. Instead, subjects' hand movements can be divided into two main parts: (i) a projectile movement which puts the hand on top of (in conditions where there is no lag), or close to (in conditions with lags) the target; and (ii) a series of compensatory tracking movements which move the hand towards the target. The increases in hand Movement Time by lag are mainly due to the increases in the duration of compensatory tracking movements which, obviously, depend on the size of the target. As a result, the effects of lag has significant interactions with target width. Since the compensatory tracking movements will only start after the hand is brought to the vicinity of the target by a projectile movement, the duration of the compensatory tracking movements are independent of target distance. Hence, the increases in Movement Time due to lags are independent of target distance. Further explanation of target-directed hand movements in the presence of lags can be found in Chung and So (1999).

In order to formulate a suitable model to describe the effects of hand-related lag on hand Movement Time (MT), a linear regression analysis was performed. The basic components in this regression model were similar to those in Equation 1 except that Index-of-Difficulty (ID) were divided into its sub-component: $Log_2(D)$ and $Log_2(2/W)$. Also, hand-related lag (L) was also added as a separate term. The resulting model is shown as follows:

$$MT = -0.56 + 0.25\ Log_2(D) + 0.1 Log_2(2/W) + 0.002\ (L) + 0.3(L*Log_2(D) + 1.03[L*log_2(2/W)] \qquad R^2=0.96$$

where D - target distance
W - target width
L - hand-related lag

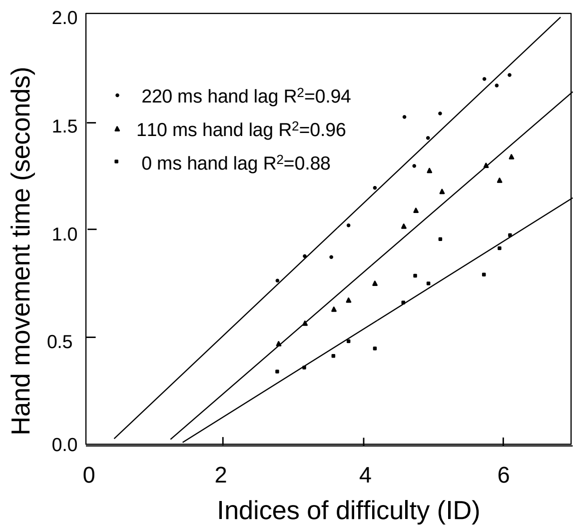

Figure 2. Target-directed discrete hand Movement Times as functions of Index-of-Difficulty (ID) (mean data obtained at three different hand-related lags

are shown).

An ANOVA analysis of the regression model indicated that all the terms had significant effects ($p<0.001$) on Movement Time (MT) except the term "$L*Log_2(D)$" ($p > 0.07$). This suggests that this term should be excluded from this regression model. This finding is consistent with the earlier ANOVA results, which report the absence of significant interaction between the effects of lag and target distance (D). After the exclusion of the term "$L*Log_2(D)$", the resulting regression model becomes:

$$MT = -0.73 + 0.28[\log_2(D)] + 0.1[\log_2(2/W)] + 0.003(L) + 1.03[L*\log_2(2/W)] \qquad R^2=0.96$$

where D - target distance
W - target width
L - hand-related lag

According to this model, an increase in target distance (D) would only have a linear effect on hand Movement Time (MT) and will not worsen the degrading effects of hand-related lag. However, a reduction of target width (W) will not only reduce the MT directly, it will also worsen the degrading effects of lags. This suggests that in designing a 'virtual' switching console for a VR system with hand-related lags, a designer should pay more attention on the size of a 'virtual' button.

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