MANUAL CONTROL WITH TIME DELAYS IN AN IMMERSIVE VIRTUAL ENVIRONMENT

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In an immersive virtual environment, inevitable time delays occur when a virtual hand responds to the hand movements of its operator. An experiment was conducted to examine the interactions among time delay, target distance, target width and movement times. Imposed hand-related time delays of 55 ms or more significantly increased the hand movement time. Data followed Fitts' law with R^2 greater than 0.75. Significant interactions were found between hand-related time delay and target width, but not between hand-related time delay and target distance. This suggests that, contrary to the common practice, the effects of target width and distance should be analyzed separately rather than in terms of a combined index-of-Difficulty.

Introduction

An immersive virtual environment (VE) system is an interactive environment in which a user can see and manipulate computer-generated objects in real time (e.g., Barfield and Furness, 1995; Kalawsky, 1993). Such systems are useful for rehabilitation training (Kiryu and So, 2008) and digital prototyping (Burdea and Coiffet, 2003). Typically, when a user moves his/her hands, the positions and orientations of the hands are used to render and update images of virtual hands. However, both the position sensing and rendering procedures take time. Consequently, when users move their hands, they cannot see the corresponding movements of the virtual hands immediately (So and Griffin, 1992; 1996; So and Chung, 2002). As technology advances, speed improvements should alleviate this discrepancy, but unfortunately, the unrelenting demand for higher resolution, finer colour gradations and lower cost has so far out-paced the advances in computer speed and the time delay problem persists. In this report, the time delay between the moment at which the hand moves and the moment at which the hand image moves is referred to as the "hand-related time delay".

In real environments, target-directed hand control movement time (MT) has been the subject of many studies (e.g., Bairda et al., 2002; Fitts and Posner, 1967; Jagacinski and Monk, 1985; Schmidt et al., 1985) and Fitts' law has been used to model MTs in the presence of time delays embedded in manual control systems (Hoffmann, 1992). In particular, Fitts' law has been modified to represent mouse-related time delays in VEs (Mackenzie and Ware, 1993; Ware and Balakrishnan, 1994). In Ware's studies, target-directed mouse pointer movement times were modelled as a function of the product of time delay and an index-of-difficulty (ID):

MT = A+B*ID+C*(ID)*(time delay)).   Equation 1

where ID = $\log_2$ (2 * target distance / target width) (Fitts and Posner, 1967).

However, studies have shown that the effects of head-related time delay on head movement time in an immersive virtual environment are not a function of the product of ID and time delay when the target width is kept constant (So *et al.*, 1999). This posts a question on whether the effects of hand-related time delays on hand movement time are also not multiplicatively proportional to ID when the target width is kept constant.

Objectives, motivations and hypotheses

This study was designed to examine the effects of, and interactions among, hand-related time delays, target width, and target distance on target-directed hand movements. A second objective was to develop another modification of Fitts' model to account for the effects of hand-related time delays on target-directed hand movements. Based on the results of a pilot study, the effects of hand-related time delays on hand movement time were hypothesized to be related to multiples of target width and not target distance. Preliminary an partial results of this study were presented at a conference (So and Chung, 2005).

Methods and Design

The virtual environment was created using the World-Tool-Kit™ software running on a Silicon Graphics Onyx (Infinite Reality II) workstation. Images of the virtual scene were displayed on a VR4 head-mounted display (HMD) with a field-of-view (FOV) of 48 degrees (horizontal) by 36 degrees (vertical). Stereo images tuned to each individual's inter-pupillary distance were presented. The position and orientation of the head and hand were measured using a Polhemus tracking system updating at 60Hz. The posture of the hand was measured using a CyberGlove™. The inherent head and hand-related time delays of the whole system were about 63 ms (comprising a 0 to 16 ms raster-scan delay and a 40 to 70 ms computational delay). All the trackers and the host computer were synchronized. The experimental room was air-conditioned and both the temperature and the background noise level were kept constant at about 22°C and below 45 dBA, respectively.

Participants, seated in front of a virtual table, were given enough time to observe the position of the target on the tabletop. They were then given one chance to move their virtual index fingers from the starting position to the target as quickly as possible (Figure 1). Tactile and force feedback was provided by placing a 'real' table at the same spatial location as the projected virtual table. The VR4 HMD was non-see-through and the subjects could not see the real environment during the experiment. At the beginning of each run, participants were asked to place their virtual fingers on the starting pad. The finishing pad (i.e., the target) would appear and the subjects were instructed to visually inspect the location of the target relative to the starting pad. They were allowed to move their heads during the visual inspection and their viewpoints in the virtual environment were updated according to their head movements. After the visual inspection, subjects were instructed to get ready to move their virtual fingers to the finishing pad as soon as the starting pad changed colour (the 'start-to-move' signal). A successful tap on the finishing pad was indicated by a change in the finishing pad's colour. The size of the virtual fingertip was about 1.5 cm (length) x 1.2 cm (width) x 0.8 cm (depth).

The experiment used four target widths (W: 1, 2, 3, 4 cm), four target distances (D: 14, 24, 41, 70 cm), and five imposed hand-related time delays (L_{hand}: 0, 55, 110, 220, 440 ms). The ranges of these independent variables were carefully selected to cover their typical values in virtual reality applications. For example, a target width of 1 cm resembles the size of a keyboard button and a target width of 4 cm is similar to the typical diameter of some larger push buttons which require fast access such as an emergency stop button. The experiment had five time delay conditions, and each condition had 16 runs exhausting the 16 combinations of D and W. The design was a within-subject full factorial experiment. The 16 runs and five time delay conditions were presented in random order. In order to detect and remove the effects of practice, the 16 runs under the same time delay condition were repeated three times before the experiment moved on to the next randomly selected condition. This practice was done in batches of 16 runs and within each batch, each run had a different combination of D and W and the order of presentation was randomized. There was a one-minute rest after each condition. In a pilot experiment, the effects of learning dissipated after two practices, therefore three practices were used in this experiment. Twelve healthy male participants took part in this experiment. All of them were experienced users of VR systems. The participants were paid HK$70 as compensation for their time. The main dependent variable was the target-directed hand movement time (MT) measured in seconds. In addition, both Reaction Time (RTs) and head displacement time histories were also measured. The positions of the virtual index finger tip were measured, and the target-directed hand-movement time (MT) was defined as the time period between the moment when the real index finger moved and the moment when the tip of the virtual finger first touched the virtual finishing pad. This definition of hand movement time (MT) is consistent with previous studies of discrete manual performance in a real environment (e.g., Hoffmann, 1992) and studies of discrete head control performance in a virtual environment (e.g., So et al., 1999).

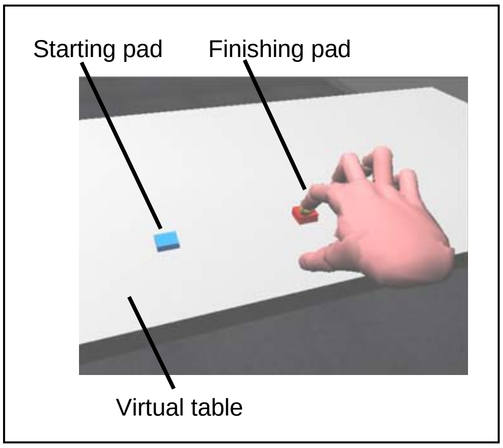

Figure 1 An subject's view of a starting pad, a finishing pad, and a 'virtual' hand. In the task, the starting pad would have disappeared to signal the start of the task. All participants were right-handed.

Results

Results of an ANOVA conducted on hand movement times indicated that practice had a significant effect ($F_{2,2568} = 9.16$, $p \leq 0.0001$). Post-hoc analyses using Student-Newman-Keuls tests (SNK) showed that MTs obtained in the first practice run were significantly longer than the rest of the data ($p \leq 0.05$). When the data from the first practice was removed, the ANOVA results no longer indicated a significant effect of practice on MTs. Consequently, data from the first practice run were excluded in all the subsequent analyses. Following the analysis techniques of Hoffmann (1992) and of Mackenzie and Ware (1993), the effects of target distance and target width were analyzed as a single effect using the index-of-difficulty. Both the hand-related time delays (L_{hand}) and the ID showed significant correlation with MTs (time delay: $F_{4,1615} = 149.9$, $p \leq 0.0001$; ID: $F_{15,1615} = 49.4$, $p \leq 0.0001$). Significant interactions between the effects of L_{hand} and the effects of ID were also found ($F_{60,1615} = 2.88$, $p \leq 0.0001$). This agrees with the findings of Hoffmann (1992) and of Mackenzie and Ware (1993). Both of those studies reported a multiplicative relationship between the effects of time delay and ID. Regression plots of the mean hand movement times (MTs) against ID indicated that within each of the five L_{hand}s, Fitts' law can be fitted to the MT data with R^2 ranging from 0.77 to 0.93 (Figure 2). As L_{hand} increased, R^2 decreased. An ANOVA was conducted to test the effects of ID on RTs and, as expected, RTs did not change significantly with different levels of ID.

Interaction effects among hand-related time delays, target distance and width were analyzed. A second ANOVA investigating the separate effects of target width (W) and target distance (D) was conducted. The results indicated that target distance (D) showed no significant interaction with L_{hand} in predicting MTs. However, there was a very significant interaction between the target width (W) and L_{hand} ($F_{12,1748}$ = 8.59, $p \leq 0.0001$). The different interactions observed for L_{hand} with D and L_{hand} with W indicate that in the presence of L_{hand}, the effects of W and D should not be analyzed in terms of a single ID effect. The lack of interaction between L_{hand} and D also suggests a lack of interaction between L_{hand} and ID if W were kept constant. Further analyses of the MT data confirmed this suggestion: no significant interaction was found between the effects of L_{hand} and ID when the target width was kept at 1 cm, 2 cm, 3 cm or 4 cm. This indicates that the previous finding of a multiplicative effect between the effects of time delays and ID may not be applicable when the target width is kept constant (Mackenzie and Ware, 1993; Hoffmann, 1992). One possible reason for the difference in findings may be differences in the test environment and apparatus. Ware and his colleagues used a PC mouse as the controller for manual operation, while participants in this experiment used their own hands to perform the tasks. In Hoffmann's experiment, the task was performed in a 'real' environment and a manually operated rotary controller was used.

Implications of the findings

The study has shown that hand-related time delays (L_{hand}) can significantly increase target-directed hand movement times in a manual operation within a virtual environment. Unlike previous studies on the effects of time delays on hand movement time, this study has demonstrated that the interaction between delays and target width (W) is different from the interaction between delays and target distance (D). This suggests that in the presence of hand-related delays, the effect of target width and the effect of target distance should not be analyzed as a single effect of an index-of-difficulty (ID).

In this study, effects of hand-related time delays only had significant interactions with target width but not target distance. As the target width gets smaller, the time taken to reach the target gets longer. This suggests that in designing virtual reality (VR) systems with inevitable time delays, it is important to avoid using small targets. Besides just making a target bigger, there are other ways to increase the size of a target. So and Griffin (2000) reported that by attaching a velocity pointer to a moving target inside a virtual environment (VE), significant improvement in tracking performance can be obtained. Further work to develop simple guidelines for VR designers to increase the tolerance of a VE to the presence of time delays is desirable. Delay compensation with manual tracking performance has been studied (So, 1997; So and Griffin, 1991, 1995, 1996, 2000). Extending those studies to discrete target-direction hand movements will be useful.

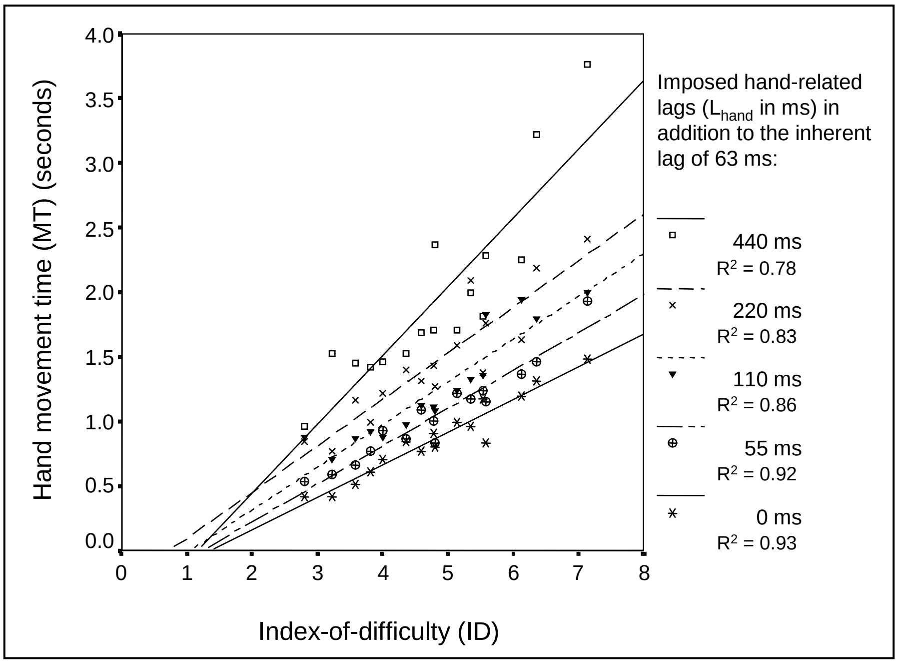

Figure 2 Regression plots of discrete target-directed hand movement times (MTs) as functions of ID with different imposed hand-related lags (0, 55, 110, 220, 440 ms in addition to a 63 ms base lag).

Conclusions

For a virtual reality system with a base time delay of 63 ms, imposed hand-related time delays of 55 ms or more can significantly increase discrete target-directed hand movement times. This suggests that virtual reality (VR) systems with response delays as small as 55ms can cause significant performance degradation. With imposed hand-related time delays from 55 ms to 440 ms, discrete target-directed hand movement times have been found to obey Fitts' law (values of R^2 have ranged from 0.77 to 0.93).

Effects of hand-related time delays have been found to interact significantly with target width, but not target distance. This suggests that in the presence of hand-related delays, the effects of target width and distance should be analyzed separately rather than combined in an index-of-difficulty.

Results of the study suggest that performance degradation with time delays worsen with the use of smaller objects. Designers of virtual environments should avoid using small objects in the presence of inevitable time delays.

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