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Sensory Motor Responses in Virtual Environments: Studying the Effects of Image Latencies for Target-directed Hand Movement

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***Abstract*—Image latencies occur when a virtual environment (VE) responds to hand movements of its operator. A study has been conducted to investigate the effects of, and interactions among, hand movement related image latencies, target distance, and target width on discrete manual control tasks in a VE. In the presence of latencies, completion times of hand movement tasks have been found to obey Fitts' law. Significant interactions were found between the effect of latency and target width, but not between the effect of latency and target distance. Results suggest that, in the presence of hand movement-related image latencies, the effects of target width and target distance should not be analyzed as a combined single effect of 'Index-of-Difficulty'.**

I. Introduction

A typical VR display includes a Head-Mounted Display (HMD) or a surround projection system such as the CAVE™ (a surround projection system for displaying Virtual Environment). When a user moves his or her hand, the position and orientation of the hand are measured and the data are used to render and update images on a Virtual Reality display. However, both the position sensing and rendering procedures take time. As a consequence, when users move their hands, they cannot see the movement of the virtual hands immediately. The time delays involved are referred to as hand-movement related image latencies.

A review of literature indicates that (i) latencies have been reported as the major factors affecting manual control performance in a Virtual Environment (VE), and (ii) findings of the few published experiments on the effects of latencies on discrete manual performance were not consistent with previous findings by the authors (e.g., Ellis *et al.*, 1997; Mackenzie and Ware, 1993; Ware and Balakrishnan, 1994; and So *et al.*, 1999). In particular, the authors hypothesized that the effects of hand-related latencies would have a multiple effect with target width and not target distance. In other words, the effects of latency would have significant interactions with effects of target width and not target distance. In order to verify the hypothesis, two experiments were conducted. The experiments investigated the effects of hand-related latencies on a discrete manual task performed in an immersive VE. The purpose was to determine the effects of, and the interactions among, hand-movement related latency, target distance, and target width. Full details of the study are reported in So and Chung (2006).

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II. Experiment One

A. Objective

The objective of Experiment one was to examine the effects of practice on discrete manual performance in the presence of latencies so as to define the number of repeated run in the design of Experiment two. In addition, this experiment also served to train the subjects for Experiment two.

B. Details

Twelve participants took part in a within-subject experiment with forty-eight manual tapping tasks. Each task required the participant to control and move the 'finger-tip' of an image of a virtual hand inside a virtual environment from point A to point B and back three times. In other words, within each task, the participants repeated the tapping movements between the two points six times. The forty-eight tasks were the factorial combinations of eight repetitions and six tapping distances (i.e., the corresponding real physical distance from virtual point A to virtual point B). The width of the virtual points A and B was 2.5 inches and the six tapping distances were 4, 8, 12, 16, 20, and 24 inches. This resulted in six index-of-difficulties (IDs) from 1.6 to 9.6 (e.g., Fitts and Posner, 1967). The range of target distance and width were chosen so that all targets were visible within the fovea view of the Head-Mounted Display (HMD) and the range of IDs was similar to those in previous studies of discrete manual performance in 'real' environment (e.g., Hoffmann, 1992).

Both the virtual points A and B and the image of the hand were three-dimensional images that were parts of a virtual environment (VE). These images were viewed through a VR4 head-mounted display (HMD). The field-of-view of the HMD was 48 degrees x 36 degrees and stereo images of the view-points of the VE were generated using World-Tool-Kit™ running on a 4-processor Silicon Graphics Infinite-Reality II workstation. The VE was stationary and had the same orientation as the real physical world. The view-point of the VE viewed on the HMD was controlled by a Polhemus six-degree head movement tracking system. To provide a tactile feedback, wooden artifacts were placed at the

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corresponding real-world positions of the virtual points A and B. Participants controlled the image of the virtual hand using a cyber-glove™ hand gesture measurement system with a Polhemus position and orientation tracker. This enables the images of the virtual hand to follow and copy the positions and orientations of the real hands of the users. Because the VE was scaled to match the real world, when the real hand travel one inch along a particular direction, the images of the virtual hands would also travel one inch in that direction inside the VE. Through out the entire experiment, an image latency of 283 ms was imposed between the moment the real hand moved and the moment the image of the virtual hand responded. Out of the 283 imposed latencies, 63 ms was the base-line latency of the virtual reality system and 220 ms was added by the experimental software. In this study, the dependent variable was the movement time of each tapping movement from the virtual point A to the virtual point B. Each participant had to perform 288 tapping movements. The movement time of each tapping movement consisted of two parts: (i) the reaction time (RT) and (ii) the movement time (MT). Previous studies have shown that RTs are invariant to the changes of 'index-of-difficulty' (ID) and latencies (e.g., Hoffmann, 1992, So et al., 1999). In this study, analyses are focused on the MT measurements.

C. *Results*

Results of ANOVAs indicate that the reaction time data are indeed not affected by changes of ID ($p>0.4$). Because the focus of Experiment two is on the effects of ID and Experiment one is a preliminary study for Experiment two to determine the number of repetitions needed for Experiment two, subsequent analyses focus on the measured movement time data only (MTs).

Results indicate that both the six repetitions of the tapping movements and the eight repetitions of the tasks had significant main effects on the measured movement times (MTs) ($p<0.001$: ANOVAs). Post-hoc analyses indicated that after removing the MT data collected for the first tapping movement of the forty-eight tasks from the twelve participants, the remaining five repetitions of the tapping movement do not have significant effect on MTs ($p>0.1$). When the data collected for the first two repetitions of the six tasks with different distances are removed, the remaining six repetitions of the tasks do not have significant effect on MTs ($p>0.1$). The dissipation of learning effects after two practices provided the basis for the use of three repetitions in the second experiment. It is anticipated that the effects of repetition in Experiment two will be less because the same twelve participants who took part in this experiment will take part in the second experiment. The observation that after the first tapping movement, participants could lock their lower arms and fingers in fix postures and perform a set of open-loop movements prompted some changes in the task procedure during the Experiment two.

III. EXPERIMENT TWO

A. *Objective*

The objective of Experiment two was to investigate the effects of, and interactions among, hand-movement-related latency (L_{hand}), target distance (D), and target width (W) on the movement times of manual tapping movements performed in a VE. The tapping movement was carried out between two virtual points (A and B) and the target distance was defined as the horizontal distance between the two points. Only the horizontal distance was counted as the target distance because the images of the two virtual points were anchored to the same physical height in the real space. The target width was defined as the width of images representing the virtual points A and B. Both points have the same sizes.

The specific hypotheses were: (i) measured hand movement time (MTs) would increase with increasing L_{hand} (H1); (ii) with a constant latency, the relationship among MT, W, and D would obey Fitts' law (Fitts and Posner, 1967) (H2), and (iii) the interaction effects between the L_{hand} & W and L_{hand} & D will be different (H3).

B. *Details*

The apparatus used was the same as that in Experiment one. During Experiment one, it had been observed that when a subject repeatedly tapped between two virtual points, the control of hand movements could be taken over by 'muscle memory' rather than visual-motor co-ordination. In other words, the visual-motor feedback task had become a type of feed-forward task. This level of skill development was to be avoided in Experiment two because the study aimed to study the effects of latencies on discrete manual performance under continuous visual feedback in a VE. In a typical virtual reality training application, most manual manipulation tasks require continuous visual feedback of 'virtual' hand and the associated virtual objects. In this experiment, the repeated tapping movements were not used. Instead, during each task, subjects were given enough time to observe where the target was and they were given one chance to move their virtual 'index' fingers on top of the finishing pad as quick as possible.

A within-subject experiment with 240 visual-motor task conditions was conducted. As described above, each task consists of visual observation and a change to move the virtual finger from point A to point B. The 240 task conditions were the factorial combinations of three repetitions, four target widths (W: 1, 2, 3, 4 cm), four target distances (D: 14, 24, 41, 70 cm), and five imposed hand movement-related latencies (L_{hand}: 0, 55, 110, 220, 440 ms). The twelve participants took part in the first experiment were invited back to take part in this experiment. The main dependent variable was also the hand movement time (MTs). More details of the experiment can be found in So and Chung (2006).

C. *Results*

After the data collected from the first repetition are removed, effects of repetition no long has a significant main effect on the measured hand movement times (MTs) (p>3.5, ANOVA). Consequently, data from the first practice were excluded in all the subsequent analyses.

Results of ANOVAs indicate that as the latency increased, MTs increased significantly (p<0.01). This supports H1. For each latency condition, Fitts' law regression equations have been successfully fitted to the MTs data as functions of IDs. This supports H2. Examinations of the interactions indicate that the effects of target distance (D) had no significant interaction with the effects of L_{hand} but there was a very significant interaction between the effects of target width (W) and L_{hand}. This supports H3 and suggests that, in the presence of L_{hand}, the effects of W and D should not be analyzed as a single effect of ID. This is an important finding because the traditional way of studying the relationships between the effects of W, D on MTs in the presence of L_{hand} was to combine W and D into ID. In the light of the current findings, this traditional approach could be wrong because a study keeping D constant and a study keeping W constant can produce two completely different relationships among MTs, L_{hand}, and IDs.

In addition to the above summarized results, a model to predict the effects of L_{hand} on MT has been developed. This model is based on the suggested approach and the effects of W and D are not combined as that of ID. Details can be found in So and Chung (2006).

IV. Conclusion

This paper presents a study conducted to investigate the effects of, and interactions among, target width, target distance, image latency on the hand movement times during visual-manual control tasks performed in a virtual environment. Results indicate that while the effects of target distance do not have a significant interaction with the effects of latency on the hand movement times, the effects of target width have significant interactions with the effects of latency. This suggests that the traditional approach to combine D and W into a single independent variable of ID when fitting Fitts' law style regression equation to MT data are not appropriate in the presence of hand movement latencies.

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