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Combined and interacting effects of hand and head movement delays on discrete manual performance in a virtual environment

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Keywords: Discrete manual performance; Head and hand movement delays; Virtual reality; Temporal response; Taxonomy of delays.

Transmission delays occur when a virtual environment responds to the hand and head movements of an operator. The effects of hand and head-related delays on discrete manual performance was investigated experimentally and compared. Imposed hand and head-related pure delays equal to or greater than 110 ms and 220 ms, respectively, significantly increased hand Movement Time (MT). The effect of hand-related delays was greater than that of head-related delays of the same magnitude. A regression model describing the combined effects of both delays on MT is reported ($R^2 = 0.95$). Analyses of the interactions among delays, target width, and distances have shown the need to adopt the traditional classification of delays into (1) control delay, and (2) display delay. The use of this taxonomy and the regression analyses to describe and explain the effects of individual and combined effects of delays on discrete target-reaching task performance in virtual environments are discussed.

1. Introduction

1.1. *Background and introduction*

Head-coupled Virtual Reality (VR) systems have been developed and used for over three decades. These systems facilitate a more natural and direct interface between a human and a computer (Sutherland 1968, Furness 1969, Woodruff *et al.* 1986, Kalawsky 1993, Carr and England 1995, Earnshaw *et al.* 1995). A head-coupled VR interface supports the natural selection of visual field-of-view (FOV) using head movements and the manual manipulation of objects using direct hand movements. With these capabilities, VR systems have been used to present computer-generated environments for training (vehicle control: Schiffler and Pinkus 1987, Pausch *et al.* 1992, Nilsson 1993, Kuhl *et al.* 1995; machine control: Lin *et al.* 1996, Johnson *et al.* 1998); entertainment (Pausch *et al.* 1996, Pierce *et al.* 1999), telematic control (Rod and Pardini 1996, Agah and Tanie 1999), scientific research (Bryson and Levit 1992), and product design (Bullinger and Fischer 1998).

Over the years, as computer technology has advanced, so has the understanding of ergonomics issues associated with head-coupled VR systems. For example, problems concerning visual perception with VR displays have been the subject of many studies (Roscoe 1987, Carr and England 1995), however, as highlighted by

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Stanney *et al.* (1998), ergonomics challenges remain in VR systems. In particular, Brooks (1999) reported that despite various research efforts, time delay problems remain as one of the ergonomics issues with VR systems. A head-coupled system needs to detect, measure, and update visual images according to head and hand movements, so a delayed response to a user's movement is inevitable. Due to the additional presentation of other computational demanding sensory information such as virtual directional sound cues (Hendrix and Barfield 1996) and tactile information (Yoshikawa *et al.* 1995), this time delay will unfortunately remain even as computational speed increases exponentially.

In a head-coupled VR system, images are usually presented on a Head-Mounted Display (HMD) or an enclosed surround display system such as CAVE™ (Cruz_neira *et al.* 1992). In a HMD, the position and orientation of a user's head are measured to maintain the correct presentation of graphics. In an enclosed surround display system, although the field-of-view of a user will respond naturally to head rotation, the translational positions of the head will still need to be measured to maintain the correct perspective of computer-generated images. Consequently, transmission delays associated with head movement may significantly affect performance in a head-coupled virtual environment. A 'head-related' delay has been defined as the time delay between the moment the head of a user moves, and the moment the computer-generated images respond (So *et al.* 1999). This delay includes the transmission delays involved in the measurement process, graphics rendering process, and display presentation process. A typical delay duration ranges from 20 ms in some military and research systems using simple symbolic displays (So and Griffin 1995) to about 70 to 150 ms in a VR research system using three-dimensional colour graphics (So 1994: 75 ms, Brooks 1999: 80–150 ms). The duration of delay primarily depends on the complexity of the graphics involved. In 1999, Brooks reported that although the typical head-related delay had been reduced from about 250 ms in 1993 to around 80 to 150 ms in 1999, it remained a problem. Besides the orientation of the head, the position, orientation, and posture of the user's hands are also measured in a VR system. These data are used to present computer-generated hands (figure 1). As a hand moves, there will be a time delay before the virtual hand can respond, an effect that has been referred to as the 'hand-related' delay (Chung and So 1999). The duration of this delay depends on the complexity of the virtual hand image and the speed of measurement of the hand's position, orientation, and posture. A 150 ms hand movement-related delay was reported by Kenyon and Afenya (1995) in their head-coupled VR system with a CAVE™ display.

In the remainder of this Introduction, literature concerning the effects of (1) head-related delays, (2) hand-related delays, and (3) combined head- and hand-related delays on discrete manual tasks in Virtual Environments (VEs) are reviewed.

1.2. *Previous studies concerning the effects of head-related delays on discrete manual task performance in VEs*

Kozak *et al.* (1993) and Kenyon and Afenya (1995) reported the problems of time delays in head-coupled Virtual Reality (VR) systems. However, the aim of their studies was to evaluate the transfer of training from a Virtual Environment (VE) to a real environment and, hence, did not study the effects of different delays. In 1990, Bryson and Fisher studied the temporal responses of an image icon presented in a VE. The position of the icon was programmed to follow the position of a tracker commonly used in VR systems (e.g. a Polhemus tracker). Different time delays were

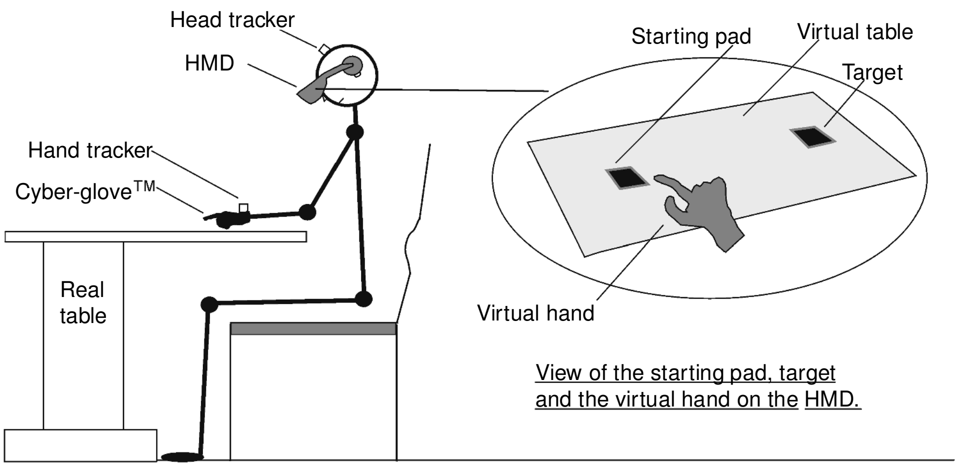

Figure 1. A diagram illustrating the view of a participant wearing a head-mounted display and moving his hand from the 'virtual' starting pad to the 'virtual' finishing pad.

imposed to slow down the response of the icon, and the position errors between the icon and the tracker were measured. The result was a set of relationships among tracker update rates, tracker velocities, and image position errors (radial displacements between the position of the icon and the position of the tracker). However, since their study only measured the dynamic response of a tracker, human performance in the presence of delays was not studied.

Two studies have investigated the effects of head-related delay on manual performance tasks in VEs. Arthur *et al.* (1993) reported a study on the effects of head-related delays in a mouse-control target search and identification task performed in a head-coupled desktop VR system. Participants wore a shutter-glass™ and watched stereoscopic images displayed on a desktop monitor. The perspective views of the images were updated according to a head position tracker mounted on the shutter-glass™. Head-related delays were found to have a multiplicative effect on the task completion times. As Arthur and his colleagues have pointed out, a head-coupled desktop VR system is different from the conventional head-coupled VR systems with Head-Mounted Displays or CAVE™. Consequently, the results from the study cannot be directly applied to an immersive VE. In 1996, Kawara and his colleagues studied the effects of head-related delays on a manual 'pick-and-place' task performed in an immersive VE presented on a HMD. Pure delays of 0, 300 and 500 ms were used but only the effects of delays on visual fatigue were measured and the effect of delay on manual performance was not reported (Kawara *et al.* 1996). Significant increase of visual fatigue was found with delays of 300 ms or more. Besides head-related delay, hand-related delay was manipulated in the same experiment, the results of which are reviewed in §1.4.

1.3. *Previous studies concerning the effects of hand-related delays on discrete manual task performance in VEs*

It is worth noting that in the field of visual-motor control research, the effects of pure delays and control lags in continuous manual-control operations in 'real' environments have been studied for almost four decades (Warrick 1949: transmission control lag; Gum and Albery 1977: system transport delay; Miller and Riley 1976: visual-motion time delay; Jewell and Clement 1984: throughput delay; Allen and DiMarco 1984: transport delay; Riccio *et al*. 1987, Levison and Papazian 1987: simulator delay). Experiments conducted with manual-control delays in discrete manual operations in 'real' environments are also numerous (Sheridan and Ferell 1963, Jagacinski and Monk 1985, Schmidth *et al*. 1985, Hoffmann 1992). Our review, however, is limited to studies of the effects of hand-related delays in a Virtual Environment (VE). A comprehensive review of the effects of delays on manual performance in the real environment can be found in Boff and Lincoln (1988).

In 1992, Friedmann *et al.* reported a simulation study indicating the potential benefits of delay compensation by a Kalman filter. The time history used in the simulation was recorded hand movements during a drum-playing session in a virtual environment. Delays were introduced into the recorded movements and the benefit of delay compensation was demonstrated through simulation. MacKenzie and Ware (1993), and Ware and Balakrishnan (1994) studied the effect of mouse-related delay on a discrete manual task viewed using a head-coupled desktop Virtual Reality (VR) System. They concluded that discrete manual performance can be degraded by mouse-related delay and the effects of delay on hand Movement Time (MT) could be modelled using a modified Fitt's Law. In particular, their results indicated that the effect of delay is a multiple of the Index-of-Difficulties (ID). This ID has been defined as the logarithm, to the base 2, of twice the ratio of target distance over target width (Fitts and Posner 1967). Ware's finding in MacKenzie and Ware (1993) and Ware and Balakrishnan (1994) is consistent with Hoffmann's study (1992) on the effects of delays on a manual task in a real environment. In 1999, the authors conducted two experiments to investigate the relationships among the effects of hand-related delays, target distance, and target width (So *et al.* 1999). The results indicated that the proposed relationship between delay and ID by Hoffmann (1992) and MacKenzie and Ware (1993) do not hold when target width is kept constant. Incidentally, target distance was kept constant in Hoffmann's study (Hoffmann 1992).

1.4. *Previous studies concerning the combined effects of head- and hand-related delays on discrete manual task performance in VEs*

In a Virtual Environment (VE), head-related delay and hand-related delay do not occur in isolation. Consequently, their combined effects and their interactions should be studied. Kawara *et al.* (1996) studied the combined effects of head- and hand-related delays on visual fatigue while performing a manual 'pick-and-place' task in an immersive VE. The task was similar to those used in Kozak *et al.* (1993), and Kenyon and Afenya (1995). Kawara and his colleagues reported that the effects of hand-related delay on visual fatigue was significantly less than that of head-related delay (Kawara *et al.* 1996). Their explanation was that hand movement is normally executed by feed-forward control without visual feedback signals and, therefore, is not affected by head-related delays. However, they did not report the effects of delays on task performance. After conducting some pilot tests, the authors observed that while performing a manual target reaching task in a VE with delays, hand movements do require visual feedback. As a result, the authors hypothesized that the effects of a hand-related delay on manual performance should be greater than that of a head-related delay with the same magnitude. An experiment conducted to test the hypothesis is presented in this paper. Ware and Balakrishnan (1994) compared the effects of head- and hand-related delays on discrete manual task performance in a head-coupled desktop VE. They reported that the effects of a mouse-related delay were significantly greater than those of head-related delays. However, as explained above, a head-coupled desktop VE is different from the conventional immersive head-coupled VE. In 1997, Watson and his colleagues reported a study of the effects of frame rate variation on manual task performance in a VE (Watson *et al.* 1997). In their study, both the effects of mean and variation of frame rate were reported. Results showed that an increase in mean frame rate from 50 ms to 100 ms significantly degraded the performance. Since a frame delay affects both head and hand movements in a VE, Watson's study could be viewed as a study of combined head- and hand-related delays with the same magnitude. However, the aim of Watson's study was to investigate the effects of delay variation and did not vary the mean head-related delay and mean hand-related delay differently.

1.5. *Summary and research questions*

Although the individual effects of hand- and head-related delays have been studied, few experiments have investigated the combined effects of the 'head-related' and 'hand-related' delays and their relative effects. From an academic point of view, the combined and interaction effects of these two types of delay will further the understanding towards human performance in a virtual environment. From an industrial point of view, understanding the relative degrading effects of the two delays and their interacting properties will enable effective applications of delay compensation technique. For example, an adaptive approach to appropriately turn on and off a delay compensation algorithm can maximize the benefits of the compensation while minimizing any unwanted side-effects such as non-unity gain and jittering (So and Griffin 1996). In this paper, an experiment investigating the individual, relative, and combined effects of head-related and hand-related delays with discrete manual operations is presented. In particular, discrete target-reaching operations were studied because most manual tasks in a Virtual Environment (VE) will involve some sort of target-reaching discrete hand movements.

2. Experiment: delays with discrete tasks

The purpose of the experiment was to investigate the combined effects of, and interactions among, head-related delay (DE_{head}), hand-related delay (DE_{hand}), target distance (D), and target width (W) on discrete manual performance in a Virtual Environment (VE). The specific hypotheses were as follows.

(1) *Hypothesis 1.* Target-directed hand movement time (MT) would increase with increasing DE_{hand},
(2) *Hypothesis 2.* For targets outside the initial fovea field-of-view of the participants, MT would increase with increasing DE_{head}, and
(3) *Hypothesis 3.* For targets initially within the initial fovea field-of-view, MT would be independent of DE_{head}.

The rationale behind Hypotheses 2 and 3 is that if a target is initially outside the fovea field-of-view, head movements will need to be made in order to search for the target and DE_{head} will affect head movement which, in turn, will affect the time taken for the hand to reach the target (i.e. MT). Two further hypotheses were proposed.

(4) *Hypothesis 4*. DE_{hand} would have a significant interaction with target width but not with target distance, and
(5) *Hypothesis 5*. The interaction patterns among DE_{hand}, W and D would be different from those among DE_{head}, W and D.

Hypothesis 4 was based on the results of previous experiments (So *et al.* 1999) and Hypothesis 5 was based on the speculation that DE_{hand} and DE_{head} would affect the manual operation in different ways.

2.1. *Method and procedure*

The experiment was a within-subject experiment conducted with 12 male participants. They were university students and staff with ages ranging from 18 to 39 years and they were paid HK$50 (about US$6.5) as compensation for their time.

Participants were asked to perform a series of discrete manual aiming tasks within a virtual environment presented in stereo using a VR4 Head-Mounted Display (742×230 colour elements per eye; 48° horizontal $\times$ 36° vertical). Two target widths (W: 2, 4 cm), six target distances (D: 14, 18, 24, 54, 62, 70 cm), three imposed head-related delays (DE_{head}: 0, 110, 220 ms), three imposed hand-related delays (DE_{hand}: 0, 110, 220 ms), and four repeated runs were used. In total, there were 432 combinations and all participants took part in the 432 tasks (i.e. a full-factorial design).

A Polhemus tracking system (Polhemus, Inc., Colchester, VT, USA) and a CyberGlove™ (Immersion Corporation, San Jose, CA, USA) were used to measure the head, hand, and finger movements of the participants. The measured head position and orientation were used to steer the view of the HMD, while the position, orientation, and finger posture of the hand were used to control the position and posture of a computer-generated 'virtual' hand (figure 1). During each task, the participants would see a virtual table projected in front of them via the HMD. On top of the virtual table, they would see a square-shaped starting pad. The participants would then be instructed to place their virtual index fingers on top of the starting pad. After 1 s, a target pad would appear and participants would be asked to visually inspect the target while keeping their virtual fingers on top of the starting pad (figure 1). This was to ensure that all participants knew where the targets were before they reached out for the targets. After the visual inspection of the target, a ready sign would appear. Shortly after the ready sign, the starting pad would change colour and the participants were instructed to move the virtual hand to the target pad as quickly as possible. When the tips of their virtual index fingers touched the target pad, the pad would change colour and the task would be over. A typical task took about 10 s. As explained above, each participant performed 432 tasks (3 $DE_{\mathrm{head}} \times 3$ $DE_{\mathrm{hand}} \times 5$ Ds $\times$ 2 Ws $\times$ 4 repeated runs). Before the 432 tasks, participants were given a series of practice tasks so that all of them became familiar with the use of the experimental VR system. The order of presenting the 432 tasks adopted a randomized block design. Conditions having the same delays were presented in blocks in random order. There were 9 blocks (3 $DE_{\mathrm{head}} \times 3$ DE_{hand}). Within each block, the 12 tasks (exhausting the combination of 2 target widths and 6 target distances) were presented in random order and the tasks were repeated four times (i.e. 36 tasks in each block). A 30-s rest was given between each block. In this experiment, the dependent variable was the target-directed hand movement time measured in seconds. This MT was defined as the time between the moment a participant moves his 'real' hand and the moment the 'virtual' hand touches the 'virtual' target. In addition, head displacement time histories were also measured.

The Virtual Environment (VE) was created using the World-Tool-Kit™ software (Sense8 Engineering Animation, Inc., Mill Valley, CA, USA) running on a Silicon Graphics Onyx (Infinite Reality II) workstation. A real table was put at the same position as the virtual table so as to provide tactile sensation when the hands touched the virtual table. The height of the table was set at about elbow level (Pheasant 1988, British Standards Institution 1990). The inherent head- and hand-related delays of the whole system were both about 63 ms. These delays consisted of the 0 to 16 ms delays associated with the raster-scan display and the 55 ms delays associated with computation, rendering and reading tracker information. The six target distances were selected so that three of them fell within the initial fovea field-of-views of the participants and the other three fell outside the initial fovea field-of-views. In other words, participants would need to move their heads in order to see the three targets with distances of 54 cm or more. This was arranged so that the interaction between the effects of delays and the location of a target relative to the fovea view of the HMD could be studied. Both the virtual starting pad and the virtual target pad were placed on the virtual table in front of the participant.

2.2. *Results*

2.2.1. *Effects of repetition, target distance, and target width*: Results of an ANOVA conducted on hand movement times (MT) indicated that repetition had a significant effect ($F(3,5124) = 28.5$, $p < 0.0001$). *Post-hoc* analyses using Student-Newman-Keuls tests (SNK) showed that MTs obtained in the first run was significantly higher than the rest of the data ($p < 0.05$). When the data from the first run was removed, the results of ANOVA indicated that repetition no longer had a significant effect on MTs ($F(2,3833) = 1.7$, $p > 0.1$, table 1). Consequently, data from first runs were excluded in all subsequent analyses. The ANOVA analysis was repeated using data from the last three repeated runs as dependent replications and there were negligible changes to the p-value results.

Table 1. Results of an ANOVA table on target-directed hand movement times (MTs) investigating the effects of repetition, DE_{hand}, DE_{head} and their two-way interactions (data from the first run had been excluded).

Source	df	ANOVA SS	Mean square	F value	$Pr > F$
Hand lag	2	194.92	97.46	332.58	0.0001
Head lag	2	23.97	11.98	40.90	0.0001
No. of repetitions	2	1.01	0.51	1.73	0.1773
Width	1	48.97	48.97	167.10	0.0001
Distance	5	314.33	62.87	214.52	0.0001
Head lag × Hand lag	4	5.51	1.38	4.70	0.0009
Head lag × Width	2	0.03	0.02	0.05	0.9470
Head lag × Distance	10	5.37	0.54	1.83	0.0501
Head lag × Repetition	4	0.99	0.25	0.85	0.4942
Head lag × Width	2	1.96	0.98	3.35	0.0353
Hand lag × Distance	10	2.68	0.27	0.92	0.5178
Hand lag × Repetition	4	1.13	0.28	0.97	0.4251
Distance × Width	5	2.90	0.58	1.98	0.0789
Model	53	603.78	11.39	38.87	0.0001
Error	3833	1123.27	0.29		
Corrected total	3886	1727.05			

Inspections of the ANOVA results (table 1) show that both the target distance (D) and width (W) had significant effects on MTs ($p<0.0001$). For each of the nine combinations of delays, regression analyses based on the standard Fitts' law equation (Fitts and Posner 1967) were conducted and the results are shown in table 2. Results indicate that, within each of the nine combinations of DE_{head} and DE_{hand}, Fitts' laws can be fitted to the MT data with regression coefficients (R^2) >0.88.

2.2.2. *Effects of head-related delays and their interaction with target distance and width*: Inspection of table 1 indicates that head-related delays, DE_{head}, significantly affected target-directed hand movement times, MTs ($F(2,3833) = 41$, $p<0.0001$). *Post-hoc* Student-Newman-Keuls (SNK) analyses showed that the effects of DE_{head} on MTs increased with delay duration and the effects were significant when the duration reached 220 ms ($p<0.05$). Results of two-way interaction analyses indicated that the effects of DE_{head} had no significant interaction with the effects of target width, W ($F(2,3833) = 0.05$, $p>0.9$) but had marginal significant interaction with the effects of target distance, D ($F(10,3833) = 1.83$, $p = 0.0501$). As the target distance (D) increased, the effects of DE_{head} increased ($p = 0.0501$). Since DE_{head} is the transmission delay of the VR system to head movement, its effects should depend on the amount of head movement. One possible explanation for the significant interaction between the effects of D and DE_{head} is that as D increases, the amount of head movement increases which, in turn, causes an increase in the effects of DE_{head}. The mean rms angular head displacements in the yaw axis for the six target distance conditions are shown in figure 2 as functions of head-related delay (DE_{head}). An inspection of the figure shows that targets with initial distances of 54 cm or more produced much higher mean rms head displacements in the yaw axis. A *post-hoc* SNK analysis confirmed that head displacements increased significantly when target distances were 54 cm or more ($p<0.05$). As explained in §2.1, targets with distances of 54 cm or more were initially outside the fovea field-of-view (FOV) of the participants. In order to test the effects of target position (i.e. inside or outside the fovea FOV) on the effects of DE_{head}, hand movement time data were divided into two groups: data obtained with targets initially inside and outside

Table 2. Results of regression analyses based on Fitts' law performed on hand movement times (MTs) obtained in each of the 9 delay conditions.

Regression equation: $MT\ (\text{s}) = A + B\ (\log_2 D) + C\ (\log_2 2/W)$

Delays (imposed on the 63 ms base delay) DE_{hand}	DE_{head}	Coefficients at the regression equation A	B	C	R^2
0 ms	0 ms	−0.483	0.237	0.096	0.93
0 ms	110 ms	−0.575	0.301	0.192	0.93
0 ms	220 ms	−1.106	0.435	0.242	0.98
110 ms	0 ms	−0.351	0.283	0.230	0.97
110 ms	110 ms	−0.378	0.302	0.192	0.94
110 ms	220 ms	−0.408	0.323	0.207	0.88
220 ms	0 ms	−0.029	0.297	0.332	0.95
220 ms	110 ms	0.007	0.308	0.294	0.94
220 ms	220 ms	0.008	0.299	0.232	0.94

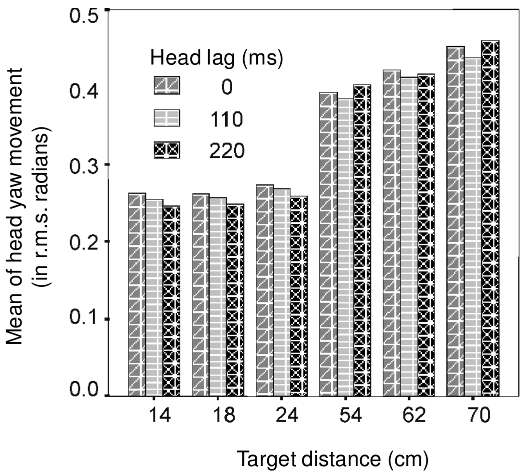

Figure 2. Mean rms head movements as functions of target distances and head-related delays (data from 12 participants and 3 repetitions). A target distance of 45 cm or more will fall outside the fovea field-of-view of the participants.

the fovea FOV. Separate ANOVAs were conducted. Results indicated that DE_{head} had significant main effects on both sets of data (within Fovea FOV: $F(2,1908) = 9.8$, $p < 0.0001$; outside Fovea FOV: $F(2,1908) = 34.6$, $p < 0.0001$). This validates Hypothesis 2 that MT would increase with increasing DE_{head} when the initial target positions were outside the fovea field-of-view. However, Hypothesis 3 that MT would be independent of DE_{head} when targets were initially within the fovea FOV was not supported. According to Hypothesis 3, a participant could reach and touch a target placed within the fovea FOV without moving his head and, hence, not be affected by the effects for DE_{head}. However, figure 2 indicates that even when targets were initially within the fovea FOV (i.e. a target distance of 24 cm or less), rms head movements in the yaw axis were not equal to zero but were about 15°. According to the comments obtained at post-experiment interviews with the participants, head movements were sometimes made to keep the target near the centre of the Head-Mounted Display (HMD) even though the targets were visible around the peripheral area of the HMD. This observation might explain the marginally significant instead of significant interactions between the effects of DE_{head} and D ($p = 0.0501$). Further ANOVA analyses were performed on hand movement time data (MTs) obtained for each of the six target distances. The results showed that DE_{head} only have significant effects on MTs for D greater than or equal to 18 cm ($p < 0.001$). This suggests that Hypothesis 3 was true only for a very short target distance ($D = 14$ cm).

The significant interaction between the effects of DE_{head} and D and the lack of interaction between the effects of DE_{head} and W indicate that when studying manual-control performance in the presence of head-related delays, the effects of W and D should be analysed in separation rather than as a combined effect of 'Index-of-Difficulty, ID' ($\mathrm{ID} = \log_{10} [2D/W]$).

2.2.3. *Effects of hand-related delays and their interaction with target distance and width*: Results of the ANOVA and the *post-hoc* Student-Newman-Keuls (SNK) analyses indicate that hand movement times increased significantly with increasing hand-related delays (DE_{hand}) of 110 ms or more ($F(2,3833) = 333$, $p < 0.0001$, ANOVA, table 1, SNK: $p < 0.05$). This validates Hypothesis 1. Inspections of table 1 indicate that the effects of target distance (D) had no significant interaction with the effects of DE_{hand} ($F(10,3833) = 0.92$, $p > 0.5$). However, there was a significant interaction between the effects of target width (W) and DE_{hand} ($F(2,3833) = 3.4$, $p < 0.05$). The different interactions between the effects of DE_{hand} and D and DE_{hand} and W were similar to the findings in Chung and So (1999) and also validate Hypothesis 4. The interaction effects support that in the presence of DE_{hand}, the effects of W and D should not be analysed as a single effect of ID.

In the previous section, the significant interaction between the effects of DE_{head} and D has been explained by the increased head displacement with increasing D. Further analyses of the raw data indicated that as D increased, rms hand displacement in the lateral axis also increased significantly (SNK: $p < 0.05$). Applying the same logic, an increase in D should increase hand displacement, which, in turn, should increase the effects of hand-related delay. However, this was not the case as there was no significant interaction between the effects of D and DE_{hand} ($p > 0.5$, table 1). In a previous publication by the same authors, target-directed hand movement was found to consist of two distinct stages: (1) a projectile movement depending on D and W but independent of DE_{hand}; and (2) a series of continuous tracking movements depending on W and DE_{hand} (Chung and So 1999). The first stage projectile hand movement is executed to get close to the target in the shortest possible time while the second stage continuous tracking movements are used to touch the target. Since the effects of delay cannot be observed before the hand moves, the initial acceleration of the projectile movement can only be determined based on the observable target distance (D) and width (W). Results in Chung and So (1999) indicated that as D increased and W decreased, the displacement and time of the projectile movement increased but the projectile movement (i.e. the first stage) was independent of DE_{hand}. Also, the time of the second stage tracking movements were found to be dependent on W and DE_{hand} but independent of D. This offers an empirical explanation for the lack of interaction effect between DE_{hand} and D but significant interaction between DE_{hand} and W reported in this study. A further review of literature indicated that this two-stage pattern is not new. In 1899, Woodworth reported that there are two types of adjustments for a target-directed hand movement: (1) an initial adjustment referring to the preparation of the hand movement to cover the entire target distance, and (2) a finer adjustment at the end of the movement to reduce the aiming error. Woodworth reported evidence that when the interval between successive movements was too short for the initial adjustment to complete, the error increased. When the interval increased beyond the time required by the initial adjustment, the error ceased to reduce. Woodworth also reported that when the interval between successive movements were small, participants using their dominant hands produced smaller aiming errors. Woodworth attributed that to more precise finer adjustments at the end of the movements through better co-ordination by the dominant hands and eyes. Woodworth's work was elaborated by Welford (1976). In his book, Welford reported that a target-directed hand movement has two phases: (1) an initial period of symmetric acceleration and deceleration—a 'distance-covering phase', and (2) a final period consisting of a series of shorter accelerations and decelerations—a 'homing-in phase'. This review of literature indicates that the two-stage pattern observed in this study and in Chung and So (1999) were, in fact, reported a century ago! Although both Woodworth (1899) and Welford (1976) did not study the individual and combined effects of different delays, the authors humbly admit that the report of the two-stage pattern is not new. This confirms an old idea in science: 'If you think you have found something new, you probably just haven't done your homework' (Schmidt *et al.* 1985: 91). In Schmidt *et al.* (1985), the period of symmetric acceleration and deceleration during the 'distance-covering phase' was studied in detail although the effects of delays was not investigated. In the rest of the paper, the two stages in the two-stage pattern will be renamed back to the original name as previously reported by Welford (1976): (1) the 'distance-covering phase', and (2) the 'homing-in phase'.

In this experiment, the pattern of interaction among DE_{hand}, D and W were the opposite of the patterns of interaction among DE_{head}, D and W (no significant interaction between DE_{hand} and D, but significant interaction between DE_{head} and D, as compared with no significant interaction between DE_{head} and W, but significant interaction between DE_{hand} and W). These results validate Hypothesis 5. One possible reason for the different interaction patterns among DE_{hand}, D and W and among DE_{head}, D and W is that the task was a manual-control task and a delay directly affecting the manual movement (i.e. DE_{hand}) should have a different, and also larger, effect on MTs when compared to a delay not directly affecting manual movement (i.e. $D\text{E}_{\text{head}}$). Further discussion on this can be found in §3.

2.2.4. *Combined effects of head and hand-related delays*: Inspection of table 1 shows that the effect of DE_{hand} on MTs was more significant than that of DE_{head} (DE_{hand}: $F(2,3833) = 333$; DE_{head}: $F(2,3833) = 41$). The average target-directed hand movement times obtained with different delay conditions is shown in table 3 with the percentage changes with respect to (1) zero imposed hand-related delay conditions, (2) zero imposed head-related delay conditions, and (3) zero imposed hand and head-

Table 3. Average hand movement times (MTs) of the nine combination of delay conditions and the percentage changes of MT as compared to the conditions with (a) 0 ms imposed hand-related delay, (b) 0 ms imposed head-related delay, and (c) 0 ms with both imposed hand and head-related delay.

Imposed hand-related delay ($D\text{E}_{\text{hand}}$)	MTs (s) [underline] and % of changes in MTs (in brackets) as compared to data at (a) 0 ms $D\text{E}_{\text{head}}$, (b) 0 ms $D\text{E}_{\text{hands}}$, (c) 0 ms with both delays. Imposed head-related delay ($D\text{E}_{\text{head}}$) (head-related delay is constant down the column): 0 ms			110 ms			220 ms		
0 ms	0.714 s			0.870 s			1.034 s		
		(a)	(+00%)		(a)	(+22%)		(a)	(+45%)
		(b)	(+00%)		(b)	(+00%)		(b)	(+00%)
		(c)	(+00%)		(c)	(+22%)		(c)	(+45%)
110 ms	1.008 s			1.095 s			1.168 s		
		(a)	(+00%)		(a)	(+ 9%)		(a)	(+16%)
		(b)	(+41%)		(b)	(+26%)		(b)	(+13%)
		(c)	(+41%)		(c)	(+53%)		(c)	(+64%)
222 ms	1.386 s			1.462 s			1.443 s		
		(a)	(+00%)		(d)	(+ 5%)		(a)	(+ 4%)
		(b)	(+94%)		(a)	(+68%)		(b)	(+40%)
		(c)	(+94%)		(b)	(+105%)		(c)	(+102%)

related delay conditions. Inspection of table 3 indicates that for the same delay duration the average effect of DE_{hand} on MT was larger than that of DE_{head} (e.g. an increase of DE_{hand} from 0 to 110 ms produced an average increase in MT of 41% and a similar increase in DE_{head} only produced a 22% increase in MT). Also, it can be observed that the influence of DE_{head} reduced as DE_{hand} increased (e.g. in the absence of imposed DE_{hand}, an increase of 220 ms DE_{head} produced a 45% increase of MT while in the presence of 220 ms imposed DE_{hand}, an increase of 220 ms DE_{head} only produced a 4% increase in MT). Results of ANOVA indicate that there was a strong interaction between the effects of DE_{head} and DE_{hand} ($F(4,3833) = 4.7$, $p < 0.001$, table 1). The interaction plot between the effects of DE_{head} and DE_{hand} is shown in figure 3. As shown in figure 3, as DE_{hand} increases, the effects of DE_{head} decrease.

3. Discussion

3.1. *Individual and combined effects of delays*

In this study, imposed head-related delay (DE_{head}) also had a significant effect on the hand movement time ($p < 0.001$, table 1). However, as reported above, the pattern of interaction effects among DE_{head}, W and D was different from that among DE_{hand}, W and D. The interaction effects among DE_{head}, W and D also disagreed with the results reported in a previous study concerning the effects of DE_{head} in a VE (So *et al.*

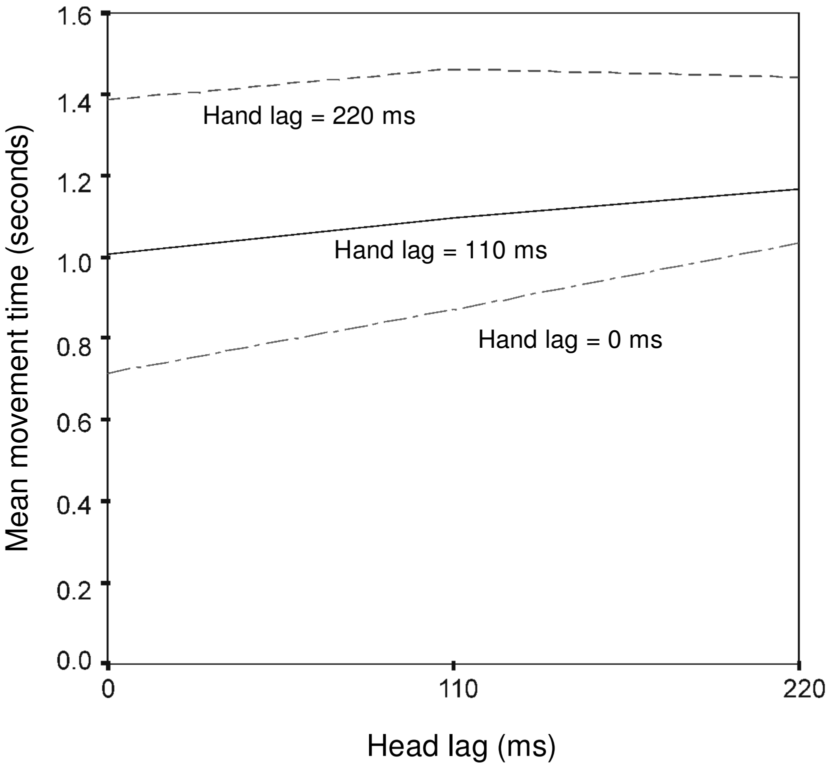

Figure 3. An interaction plot illustrates the interaction between the effects of head-related delay (DE_{head}) and the effects of hand-related delays (DE_{hand}) on target-directed manual movement times (MTs).

1999). In that study, the effects of DE_{head} had a significant interaction with W but not with D. In the present study, the effects of DE_{head} had a significant interaction with D but not with W. One possible reason for the opposite patterns of interactions may be the difference in the tasks: in the present study, manual-control tasks were studied and in So *et al.* (1999), head-control tasks were studied.

Further comparison reveals that the way DE_{hand} affected manual-control tasks in this study is similar to the way DE_{head} affected head-control tasks reported in So *et al.* (1999). This suggests that the effects of a delay depend on whether the associated body-part is controlling the task. Consequently, in addition to the classification of delays into head-related delays and hand-related delays, it seems appropriate to also adopt the traditional classification of delays into (1) control delays, and (2) display delays. In this study, a control delay refers to a delay that is directly associated with a control movement and a display delay refers to a delay that is not associated with the control movement but may affect the displayed information of the control movement. In other words, the effects of a control delay are unavoidable during a control movement while the effects of a display delay can be avoided. For example, during a manual-control task in a VE, a DE_{hand} is referred to as a control delay because it is associated with the manual movement and its effects are unavoidable. For the same task, a DE_{head} is referred to as a display delay because it is not associated with manual movement and can be avoided if the operator keeps his head still. The idea of classifying delays into control and display delays is not new. Garvey *et al.* (1957) separated the two types of delays and reported differential effects between a control and a display delay. It should be noted that in this study, the effects of both control and display delays are observable via the head-mounted display. An operator-in-the-loop model of this study is shown in figure 4. This figure illustrates the occurrence of DE_{head} (a display delay) and DE_{hand} (a control delay) in this experiment.

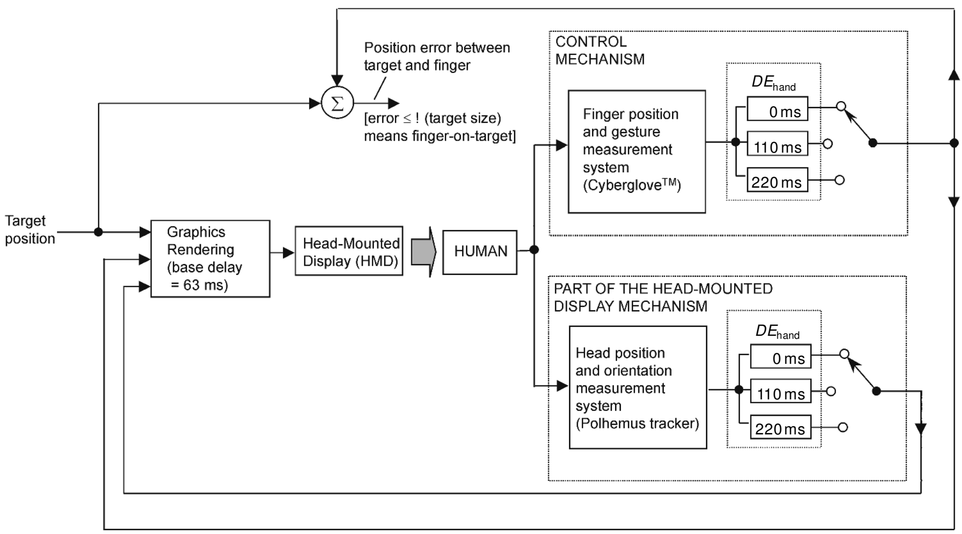

Figure 4. An operator-in-the-loop model illustrating the occurrence of control delays (hand-related delays, DE_{hand}) and display delays (head-related delays, DE_{head}) in this study.

3.2. *The use of the proposed taxonomy and regression analyses to predict the combined effects of delays*

As indicated in table 3 and explained in §2.2.4, DE_{hand} has a greater effect on manual task performance than DE_{head} of the same delay duration. This finding is consistent with the proposed taxonomy of delay as (1) control delay, and (2) display delay. The former has a direct and unavoidable effect on the hand movement and, logically, should have a greater effect on performance.

Regression analyses have been conducted to model the target-directed manual Movement Times (MT) as functions of target width (W), target distance (D), head-related delays (DE_{head}), hand-related delays (DE_{hand}), and the significant two-way interaction terms between delays with W, and delays with D. Logarithms of D and W (i.e. $\log_2(D)$, $\log_2(2/W)$) were used so as to maintain the consistency between the results in this paper and those in the previous studies using 'Index-of-difficulties' (ID) (Hoffmann 1992, MacKenzie and Ware 1993). ID is equal to $\log_2(2D/W)$. The result of the regression is as follows.

$$\begin{aligned} \mathrm{MT} = & -0.6544 + 0.2496 \log_2(D) + 0.1422 \log_2(2/W) + 2.724\ (DE_{\mathrm{hand}}) \\ & + 0.4967\ (DE_{\mathrm{hand}} \times \log_2(2/W)) - 0.9899\ (DE_{\mathrm{head}}) \\ & + 0.3636\ (DE_{\mathrm{head}} \times \log_2(D)) \qquad R^2 = 0.94 \end{aligned} \tag{1}$$

Besides the significant interaction between DE_{hand} and W, and DE_{head} and D, the ANOVA results also indicate that there is a significant interaction between DE_{hand} and DE_{head} (table 1). Instead of continuously adding extra terms to the regression model, a stepwise regression has been performed. The terms, DE_{hand}, DE_{head}, $\log_2(2/W)$, $\log_2(D)$, and all of their two-way interaction terms are added. The leaving and entry level of the stepwise regression has been set at the 5% significance level. The result of the stepwise regression analysis is shown in table 4 and the model is as follows.

$$\begin{aligned} \mathrm{MT} = & -0.8176 + 3.4684\ DE_{\mathrm{hand}} + 0.1423\ \mathrm{Log}_2(2/W) + 0.2573\ \mathrm{Log}_2(D) \\ & + 4.5139\ DE_{\mathrm{hand}} \times DE_{\mathrm{head}} + 0.3168\ DE_{\mathrm{head}} \times \mathrm{Log}_2(D) \\ & + 0.4963\ DE_{\mathrm{hand}} \times \mathrm{Log}_2(2/W) \qquad R^2 = 0.95 \end{aligned} \tag{2}$$

Table 4. Results of a step wise regression analysis to model target-directed hand movement time (MT) as a function of target width (W), target distance (D), head-related delay (DE_{head}), hand-related delay (DE_{hand}) and their two-way interaction terms.

Variable	Parameter estimate	Standard error	Type II Sum of squares	F value	Probability > ITI
Intercept	−0.8176	0.0547	65.7391	233.34	0.0001
DE_{hand}	3.4684	0.2177	74.7012	253.79	0.0001
$\log_2(2/W)$	0.1423	0.0364	4.4958	15.27	0.0001
$\log_2(D)$	0.2573	0.0114	151.224	513.77	0.0001
$DE_{\mathrm{hand}} \times DE_{\mathrm{head}}$	−4.5139	1.0256	5.7022	19.37	0.0001
$DE_{\mathrm{head}} \times \log_2(D)$	0.3168	0.0374	21.0935	71.66	0.0001
$DE_{\mathrm{hand}} \times \log_2(2/W)$	0.4963	0.1938	1.9304	6.56	0.0105

Interestingly, the term '$DE_{\mathrm{head}} \times DE_{\mathrm{hand}}$' has a negative coefficient. This is consistent with the significant negative interaction between the head and hand-related delay as illustrated in figure 3 and shown in the ANOVA analysis (table 1).

Inspection of table 4 indicates that the term 'DE_{head}' has been removed from the stepwise regression model because of the insignificant level from the ANOR analysis. As the regression analyses were conducted on the mean data, this should not be interpreted as DE_{head} had no significant effect on MTs. A possible reason for the lack of significant contribution by the term 'DE_{head}' in the regression equation 2 may be due to the dominating effect by the term '$L_{\mathrm{head}} \times \mathrm{Log}_2(D)$'. The results of ANOVA indicate a marginally significant interaction between the effects of DE_{head} and D ($p = 0.0501$, table 1). Since the effects of DE_{head} depend on the effects of D, therefore, when both the terms 'DE_{head}' and '$DE_{\mathrm{head}} \times \mathrm{Log}_2(D)$' appear in the same regression model, the contribution from the term 'DE_{head}' may become insignificant.

3.3. *Implications of the findings*

3.3.1. *General implications*: The study has shown that both DE_{head} and DE_{hand} can significantly increase target-directed hand movement times in a manual operation within a virtual environment (VE). The interactions between delays and target width (W), and between delays and target distance (D) have also been found to be different. In particular, the significant interactions between the effects of DE_{hand} and W indicates that if a VE has a long DE_{hand}, a VE designer should avoid the use of small virtual buttons. On the other hand, in the presence of a small DE_{hand} but a long DE_{head}, the size of a virtual button is less critical than the distance that a hand has to travel in order to manually press the virtual button. In other words, the positioning of the virtual button will require more attention in the presence of long DE_{head}. While understanding the relative influence of W and D in the presence of DE_{hand} and DE_{head} is important to VE designers, the ability to predict the effects of delays, W and D on the time taken to press a 'virtual' button is also critical. This study proposed a regression model to predict the combined effects of DE_{hand} and DE_{head} ($R^2 = 0.95$). Furthermore, the discovery of the significantly larger effect of DE_{hand} than DE_{head} on discrete manual operation time (MT) would help the VE designer to allocate the appropriate computing resources.

3.3.2. *Taxonomy of delays and its application to describe the effects of delays*: As discussed in §3.1, in this study a taxonomy of control and display delays is adopted to explain the differences between the interaction effects among DE_{hand}, W and D and among DE_{head}, W and D. This taxonomy classifies delays into two categories: (1) control delay, and (2) display delay. When a delay is classified as a control delay, the mechanism at which it will directly affect the control movement will follow the 'two-stage' model discussed in §2.2.3. This model explains and predicts the significant interaction between a control delay and W, and the lack of interaction between a control delay and D. For example, the effects of DE_{hand} in this study and the effects of DE_{head} in So *et al.* (1999) followed a similar interaction pattern: having significant interactions with the effects of W and not D. In both cases, the delays were control delays. If a delay is a display delay, however, this interaction pattern is not found. This is evidenced by the different interaction patterns among DE_{head} (a display delay), W and D, and among DE_{hand} (a control delay), W and D. Further evidence is found in the different interaction patterns among DE_{head}, W and D in this study and among DE_{head}, W and D in So *et al.* (1999). Although both delays were head-related delays, in this study, DE_{head} was a display delay and in So *et al.* (1999), DE_{head} was a control delay. Consequently, using the taxonomy of delays, equation (2) can be generalized as:

$$
\begin{aligned}
\mathrm{MT} = & -0.8176 + 3.4684\ DE_{\mathrm{control}} + 0.1423\ \mathrm{Log}_2(2/W) + 0.2573\ \mathrm{Log}_2(D) \\
& + 4.5139\ DE_{\mathrm{control}} \times DE_{\mathrm{display}} + 0.3168\ DE_{\mathrm{display}} \times \mathrm{Log}_2(D) \\
& + 0.4963\ DE_{\mathrm{control}} \times \mathrm{Log}_2(2/W) \qquad R^2 = 0.95
\end{aligned} \tag{3}
$$

where DE_{control} is the control delay, and
DE_{display} is the display delay.

3.3.3. *Towards an adaptive management system of delay compensation schemes*: - Studies of ways to compensate for the effects of delays in a VR system have been many (Kalman filters: Friedmann *et al.* 1992; use of multiple processors: Wioka 1995; hardware and software reorganization: Jacoby *et al.* 1996; adaptive filters: Albrecht 1989; image deflection: So and Griffin 1992; phase-lead filters: So and Griffin 1996). These have successfully demonstrated the benefits of many delay compensation schemes. A review of these studies indicates that there is a general assumption that in the presence of delays a delay compensation scheme would be needed at all times. The results of this study suggest that with discrete manual operation in the presence of delays, delay compensation schemes may not be needed for certain delays during specific time intervals. For example, the 'two-stage' model predicts that control delays (e.g. DE_{hand} or DE_{head}) only affect the control movements (e.g. manual-control movements or head-control movements, respectively) during the second stage (i.e. the 'homing-in phase'). Consequently, the delay compensation scheme for control delays can be turned off during the first stage (the 'distance-covering' phase) of discrete control movements so as to minimize any unwanted side-effects associated with delay compensation (e.g. greater than unity gain at some high frequencies: So and Griffin 1996). The actual implementation will, of course, require further study.

In addition, this study investigated the effects of DE_{head} and DE_{hand} and classified them into two types of delays: (1) control delay, and (2) non-control delay. Results indicate that control delays had a greater effect on task performance than non-control delays with the same magnitudes. This suggests that, in the absence of adequate resources, efforts in delay compensation should focus on control delays.

4. Conclusion, limitations and recommendations

Movement times with a manual target reaching task increased significantly with increasing imposed hand movement-related delays (DE_{hand}) of 110 ms or more ($p<0.05$, ANOVA with *post-hoc* SNK) and imposed head movement-related delays (DE_{head}) of 220 ms or more ($p<0.05$, ANOVA with *post-hoc* SNK).

Different patterns of interaction effects among DE_{head}, W and D and among DE_{hand}, W and D were found. Similar to previous findings, significant interaction was found between the effects of DE_{hand} and target width (W) but not between DE_{hand} and target distance (D). On the other hand, the effects of DE_{head} had a significant interaction with D but not with W. Explanations of these differences have led to the adoption of a traditional taxonomy of control delay and display delay. Using this taxonomy and the taxonomy of head and hand-related delays, a general regression equation to predict the target-directed hand movement times as a function of W, D, DE_{hand} (a control delay), and DE_{head} (a display delay) is reported. This regression equation has a level of R^2 equal to 0.95 when fitted to the mean data from 12 participants.

Both DE_{hand} and DE_{head} were found to have different interaction effects with W and D. This suggests that in addition to analysing the combined the effects of W and D as a single effect of 'Index-of-Difficulty' (ID), where ID = $\log_2(2D/W)$, individual effects of W and D should also be analysed because they have different interaction effects with delays.

This study investigated the effects of imposed delays up to 220 ms, target widths ranging from 2 to 4 cm and distances ranging from 14 to 70 cm. Although these values represent the typical ranges associated with a virtual reality system, none the less, they impose a limitation on the findings. Further studies to test the extendibility of these findings are desirable. Moreover, this paper focused on the effects of delays on discrete target-directed manual operations. Future studies should also include continuous manual tracking operations in a virtual environment.

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