Quantification of Adaptation to Virtual-Eye Location In See-Thru Head-Mounted Displays

Jannick P. Rolland
Department of Computer Science
University of North Carolina at Chapel Hill
Chapel Hill, NC 27599-3175, USA
+1-919-962-1901
rolland@cs.unc.edu

Frank A. Biocca
Center for Research in
Journalism and Mass Communication
University of North Carolina at Chapel Hill
Chapel Hill, NC 27599-3365, USA
+1-919-966-7024
fbiocca@email.unc.edu

Todd Barlow
Department of Psychology
North Carolina State University
Raleigh, NC 27695-7801

Anantha Kancherla
Department of Computer Science
University of North Carolina at Chapel Hill
Chapel Hill, NC 27599, USA

ABSTRACT

An experiment was conducted on the effect of a prototype see-thru head-mounted display (HMD) on visuo-motor adaptation. When wearing video see- thru HMDs in augmented reality systems, subjects see the world around them through a pair of head-mounted video cameras. The study looked at the effects of sensory rearrangement caused by a HMD design that displaces the user's "virtual" eye position forward (165 mm) and up (62 mm) toward the spatial position of the cameras. Measures of hand-eye coordination and speed on a manual task revealed substantial perceptual costs of the eye displacement, but also evidence of adaptation. Upon first wearing the video see-thru HMD, subjects' pointing errors increased significantly along the spatial dimensions displaced (the y and z dimensions). Speed of performance on a manual task decreased by 43% compared to baseline performance. Pointing accuracy improved by about a 1/3 as subjects adapted to the sensory rearrangement but did not reach baseline performance. When subjects removed the see-thru HMD there was evidence that their hand-eye coordination had been altered by the see-thru HMD. Negative aftereffects were observed in the form of greater errors in pointing accuracy compared to baseline. Although these effects are temporary, the results may have serious practical implications for the use of see-thru HMDs by user populations who depend on accurate hand-eye coordination such as surgeons.

1. INTRODUCTION

Nowhere is the promise of see-thru head-mounted displays (HMDs) and augmented reality more exciting than in medical imaging applications. "Medical Imaging, since its birth, has provided a valuable and yet non-surgical possibility to see what was unseen before: the internal world of the human body" [24, p14]. See-thru HMDs will take us one step further by simulating x-ray vision -- the internal world of the human body will be seen superimposed on the patient. Doctors will not divert their vision to a side monitor or viewing screen to see inside a patient's body. The virtual image of the internal organs and the real body of the patient will be merged. Doctors have always used natural observation of the body for diagnosis. Now that natural ability to observe the symptomology of a body will be extended and augmented by fusing normal observation with the visualizing power of the x-ray, the magnetic resonance machine, and the ultrasound machine. At least, that is the vision.

But a number of design challenges must be overcome before the promise of see-thru HMDs becomes reality. One of the challenges of such devices is providing depth information that accurately merges the virtual scene with the real scene. As we will see in this study, another is building a system that minimizes sensory rearrangement and the need for adaptation.

Two approaches to hardware design are now common. Real and virtual views of the world can be merged either: 1) via a semi-transparent mirror as with optical see-thru HMDs [4, 2, 6, 19], or 2) via video cameras mounted on the helmet as with video see-thru HMDs [1]. A discussion of design issues and the relative merits of each approach can be found in one of our recent studies [20].

This paper will describe the consequences of one key design feature of existing video see-thru HMDs -- *visual displacement* of the user's eyes to a virtual position -- the

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entrance pupil of the HMD's cameras. We report on an experimental study of adaptation to visual displacement using a video see- through system designed and built at the University of North Carolina at Chapel Hill [7].

2. SENSORY REARRANGEMENT, INTERSENSORY CONFLICT AND ADAPTATION TO VIRTUAL ENVIRONMENTS

Immersive virtual environment (VE) and telepresence systems are likely to induce some form of sensory rearrangement for the foreseeable future. Video see-thru head-mounted displays are a good example of a virtual reality (VR) component that requires some form of sensory rearrangement. Sensory rearrangement is a change in the normal relationship between body movements and the resulting inflow of sensation to the central nervous system. It can also result from discoordination of one sensory inflow pattern with that of another sense -- also known as intersensory conflict [15, 17]. In VEs, sensory rearrangement and intersensory conflict can result from a discoordination of displays to the various senses. According to Welch [21], "it is not so much the absence of certain stimuli that causes serious perceptual and behavioral difficulties with telesystems, but the presence of intersensory discrepancies, such as mismatches between sensory modalities and delays of sensory feedback" (p. 1).

Intersensory conflict puts a stress on the user's body, especially when the conflict involves the vestibular system [16]. The stress has cognitive, behavioral, and physiological manifestations. For example, performance is slowed down immediately after entering a HMD-based virtual environment. Movements are short and tentative. The user may be slightly uncoordinated. Reaching behavior is uncertain and inaccurate.

The heightened effects of intersensory conflict and rearrangement can also manifest themselves as the physiological reactions of simulation sickness [3]. During extended use, users may experience sweating, eye strain, stomach awareness, and vomiting [11]. To minimize the noxious effects, susceptible users may limit their movements and actions to minimize the experience of intersensory conflict. This is a concern in all training environments. Inappropriate behaviors learned in response to the simulator can negatively transfer to the real environment where they are inappropriate.

In this human factors study we wanted to explore how a user's motor system would adapt to VE induced sensory conflict between the visual and kinesthetic-proprioceptive systems. We focused on the relationship between the eyes and the hands because intersensory conflict between vision and sensed hand position (proprioception) is critical to performance in VEs. A central component of medical, military, and other training systems is learning subtle, coordinated hand-eye movements.

2.1. Research Questions

The problem of adaptation is particularly important to the practical problem of see-thru HMD design. It is difficult, if not impossible, for video-based see-thru HMDs to perfectly match the natural viewpoint of the user without trading for field of view (FOV) [7]. Therefore, for large FOV systems, some adaptation will most likely be necessary. But, inevitably, there will be some perceptual costs. What are they?

This study sought to answer the following questions:

How much will user motor performance deteriorate because the present design of video see-thru head-mounted displays displaces the eyes forward and upward?

We predicted that the intersensory conflict initiated by the visual displacement of our see-thru HMD will extract some cost on motor performance. We were interested in getting an *exact quantitative measure* of the performance cost as a benchmark that can be used to compare the human factors performance of future designs of see-thru HMDs. We also wanted an estimate of how the cognitive and motor cost would be lessened over time by practice and adaptation to the eye displacement.

Will users adapt to see-thru head-mounted displays and, if so, how quickly?

The extensive literature on adaptation [18,22] -- especially research on prism displacement -- suggests that users should adapt. But much of the relevant research involves adaptation to prism goggles that displace vision to the side [e.g., 8, 18 , 5] while our video see-thru HMD displaces the eyes to a spot higher and further out than the natural location of the eyes. It was a practical design question to see how *quickly* and *fully* users would adapt to this unnatural eye location.

Will adaptation to see-thru HMDs lead to negative aftereffects, and what is the exact extent of those aftereffects?

If users adapt to the altered eye location of the video see-thru HMD, then the users' perceptual systems might be miscalibrated for the real world once they remove the see-thru HMD. This negative aftereffect might be manifested by altered visuo-motor coordination. Again, the literature on prism adaptation suggests that negative aftereffects were

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likely [13, 22].

The presence of negative aftereffects has tremendous practical significance for the use of VEs, especially in medical applications. Consider, for a moment, the use of see-thru HMDs by surgeons. Some form of safety protocol would be necessary if use of a video see-thru HMD were to temporarily alter the hand-eye coordination of a surgeon! But the issue of negative aftereffects extends to many other VR applications as well. What detrimental negative aftereffects might influence user performance in applications requiring high levels of hand-eye coordination: e.g., engine repair, athletics, weapon aiming.

If this study indicates that some perceptual cost is evident, a program of gradual user immersion and adaptation might reduce these to tolerable limits [12, 21] or promote dual adaptation [14, 23] to the natural and virtual world.

3. METHOD

This adaptation study involved an experiment. The experiment used a 3 X 2 mixed, experimental design with three within-subjects and two between-subjects levels. The main within-subjects factor was type of HMD. The three levels of this factor were:

1) baseline task measures using *no HMD*,
2) tasks using the *see-thru HMD*, and
3) the same tasks using a *control-model of the HMD* (see description in apparatus section below).

The between subjects factor was the order in which the subjects used the HMDs: see-thru HMD or the control HMD was used first. The dependent measures were: (a) time to complete a manual task (enter pegs in a pegboard) and (b) pointing accuracy (x, y, z coordinate space) in a pair of open loop (no feedback) pointing tasks.

3.1. Subjects

Fourteen subjects participated in the study, 12 were males and 2 were females. All subjects were right handed and had an interpupillary distance (IPD) of 64 mm (+/- 1mm). The latter requirement was set to match the parameters of the equipment as described in the next section. Seven had no previous experience, 1 had very little experience, 4 had some experience, and 2 had a lot of experience with HMDs. All subjects had 20/20 vision or corrected vision.

3.2. Apparatus & Measures

Video see-thru head-mounted display. The study focused on the adaptation effects of UNC's video see-thru HMD, especially the effect of eye displacement to a "virtual" location (See Figure 1). The main components of the system are a flight helmet from Virtual Research, opaque HMD using LEEP optics [10], and two miniature custom made fisheye lens video cameras. Viewers see the real world through these cameras which are located 62 mm higher and 165 mm forward from the viewer's natural eye point (see Figure 2). The cameras are laterally separated by 64 mm, which was set according to the separation of the LEEP optics of the viewer itself. The fisheye lenses were custom designed and built to match the FOV of the LEEP optics when integrated in the flight helmet, and to precisely pre compensate the optical distortion of the optical viewer as described by Edwards et al. [7]

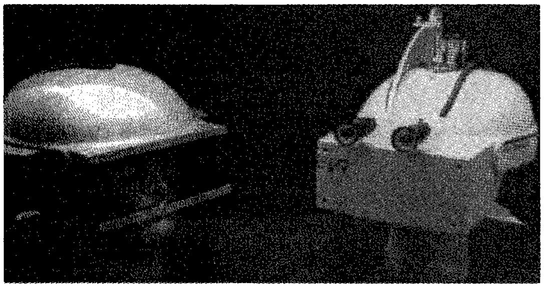


Figure 1: On the right is UNC's see-thru HMD used in the experiment. Note the camera located on the top of the helmet. On the left is a control HMD also used in the study. The control HMD was designed to match the effects of the weight and field of view of the test HMD, but without any visual displacement.

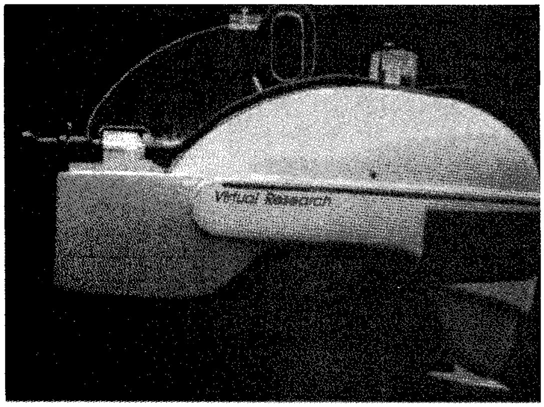
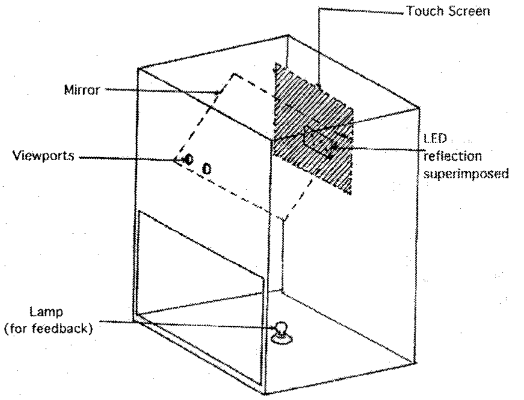
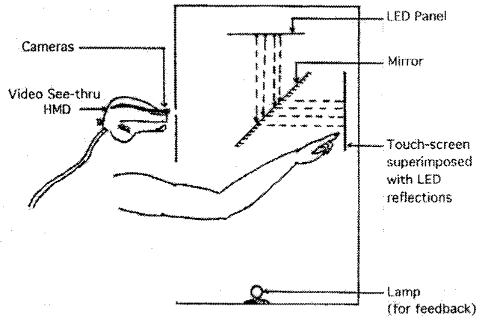


Figure 2: This picture shows the exact location of the cameras on the see-thru HMD: 62 mm higher, and 165 mm forward from the viewers natural eyepoint.

Control head-mounted display. The control HMD -- also shown in Figure 1 -- was designed to control for the effects of the weight and field of view of the test HMD on task performance. The control HMD matched the weight (7 lb.), and field of view (73.7 x 60.8 dg.) of the see-thru HMD. The actual field of view for each subject varied depending the size of the subject's head since the subject's eyes varied in their distance to the window. Our estimates calculated that the field of view of the control HMD would be withing 10% on the X dimension and approximately 11% on the Y dimension. Further, we estimated that the field of view would be smaller and the bias, therefore, would be against any performance advantage for the control-HMD. Beside equating the two HMDs in weight, the location of the center of gravity of both devices was matched.



3 (a)



3 (b)

Figure 3: Diagram of the X-Y pointing accuracy measure which allowed users to point straight ahead at an object without seeing their hand. This light-sealed box had an opening at the bottom (See 3a). Subjects looked through view ports to see one of 4 LEDs reflected off a 45 degree two-way mirror (See 3b). To the subjects, the LEDs appeared to shine from the back of the box. Subjects touched the virtual LEDs without seeing their hands and receiving feedback. Their pointing accuracy was recorded on a touch screen as X-Y coordinates.

Open Loop X-Y Pointing Accuracy Measure. Studies of adaptation require accurate, independent measures of coordination of visual spatial position and haptic/proprioceptive location. The X-Y pointing accuracy measure used in this study was an improved version of a reliable and valid measure of adaptation with a long history [e.g., 9]. Viewing through a pair of holes, subjects saw one of four, randomly lit, red LED lights inside the dark interior of a light sealed box (Figure 3). Subjects were instructed to touch the light. A calibrated touch screen captured the exact location touched and provided a measure of X-Y pointing error. A mirror set at 45 degrees gave the subjects the illusion of seeing a light straight in front of them while preventing them from seeing their hand. This feature kept subjects from using sight of their finger to "home in" on the target or from obtaining feedback as to their accuracy.

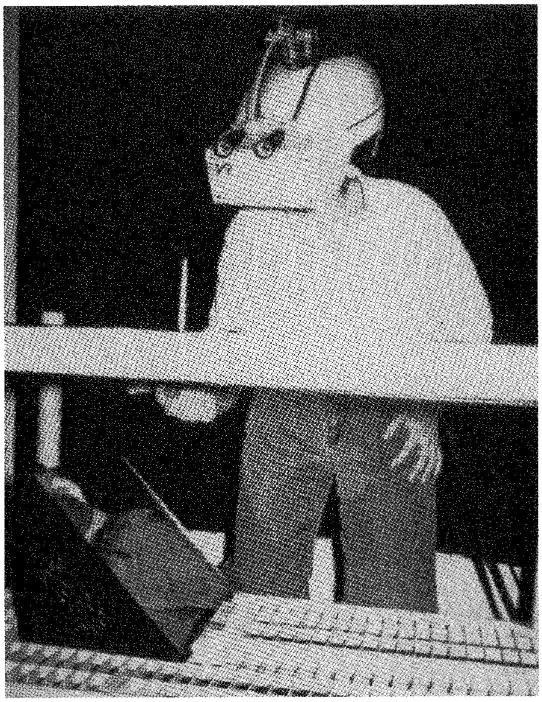


Figure 4. Representation of the measure of pointing accuracy along the Z (depth) axis. Subjects pointed at the location of the white peg underneath a shelf. Subjects received no tactile or visual feedback of their pointing accuracy. A mirror at 45° allowed data recording using a video camera.

Open Loop Z Pointing Accuracy Measure. This apparatus measured pointing accuracy along the Z axis. Subjects were seated in front of a dark shelf from which a white rod protruded as shown in Figure 4. The subject's task was to touch the point on the bottom of the shelf where the rod would protrude if pushed through the shelf. The shelf prevented subjects from seeing their hand and gauging their accuracy (no feedback). Their pointing accuracy was recorded by a camera aimed at a polar grid pasted on the bottom of the shelf.

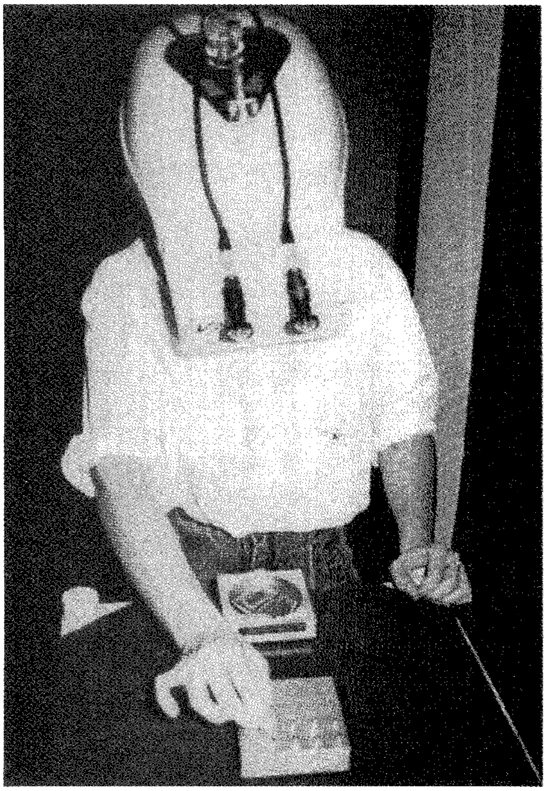


Figure 5. This pegboard task is a standard measure of manual dexterity and hand-eye coordination. In this experiment it also gave subjects immediate sensory feedback of the discrepancy between the visual sense of spatial location and their kinesthetic-proprioceptive sense of location, causing a recalibration of the latter.

Pegboard Task. This is a standardized test of manual dexterity (Lafayette Pegboard, model 32027). See Figure 5. The bowl of pegs was placed in front of the subjects and the board was 1 ft. away from the bowl.

3.3. Procedure

The order of the experimental procedure is outlined in Table 1. Following instructions various physiological and behavioral trait measurements were taken (interpupilary distance, depth perception, previous exposure to HMDs). These are not reported here.

1. Baseline performance (no HMD)
   X,Y,Z measures + task measures
2. Performancs wearing see-thru HMD or control HMD first
   X,Y,Z measures + task measures + X,Y,Z measures
3. After-effects (no HMD)
   X,Y,Z measures
4. Performance wearing alternate HMD (control or see-thru)
   X,Y,Z measures + task measures + X,Y,Z measures
5. After-effects (no HMD)
   X,Y,Z measures

Table 1. Experimental Procedure.

Baseline Procedure. Prior to putting on any HMD, subjects were measured for their baseline performance on pointing accuracy (5 trials each) and speed on the pegboard task (10 trials). For each pegboard trial, subjects began by pressing the button on a stopwatch. After they inserted all the pegs in a left-to-right and top to bottom order, the subject turned off the stopwatch. The experimenter recorded the time. Subjects could not see the face of the stopwatch, nor were they given any feedback about their performance.

HMD Procedure. Depending on the order to which subjects had been assigned, subjects either put on the see-thru HMD or the control HMD following the baseline tasks. Subjects were pretested on the pointing accuracy measures (pretest X,Y,Z measures: 5 trials each). Subjects then performed 10 timed trials of the pegboard task following the same procedure used for baseline measurement before putting on a HMD. After 10 trials of the pegboard task, subjects were measured once again for their pointing accuracy while still wearing the HMD (posttest X,Y,Z measures: 5 trials each). Subjects removed the HMD and were then measured for the presence of visuo-motor aftereffects using the pointing accuracy measures (aftereffect X,Y,Z measures: 5 trials each).

Following a 5 minute rest, subjects repeated the same sequence of tasks and measures wearing the other HMD. If they wore the see-thru HMD helmet in the first part of the experiment, they now wore the control HMD and vice-versa.

After the pretest, task, and posttest using the other HMD, subjects removed the HMD and were again measured for the presence of visuo-motor aftereffects using the pointing accuracy measures.

After the experiment subjects were treated to a sequence of closed loop (feedback) trials of the X-Y pointing measure to recalibrate their visuo-motor coordination to normal. They then filled out a short simulation sickness questionnaire.

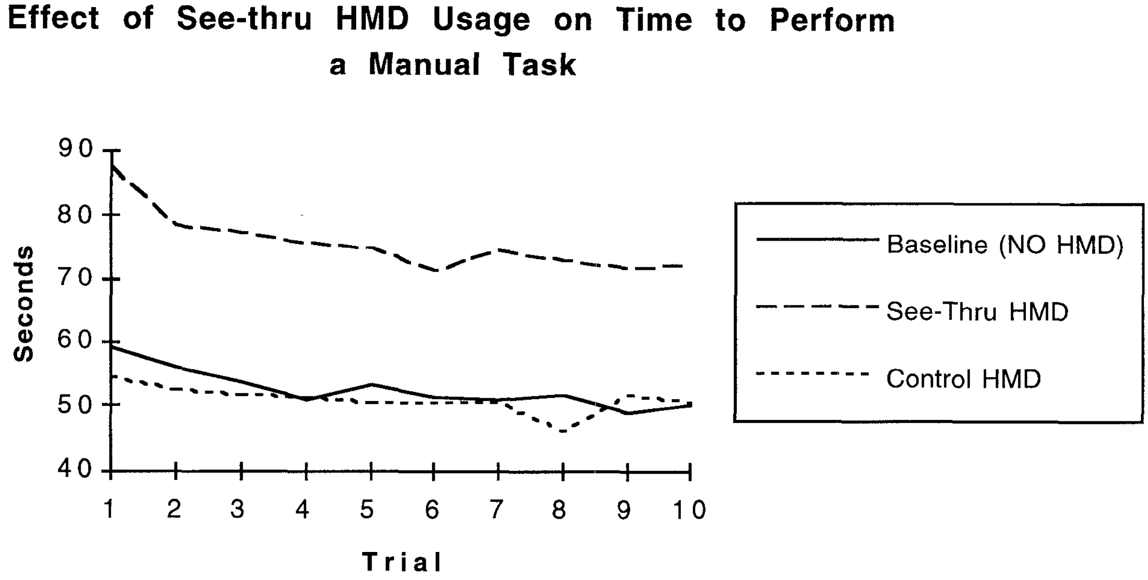


Figure 6. Effects of video see-thru HMD usage on time to perform a manual Task.

4. RESULTS

4.1. Effect of See-Thru HMD Usage on Manual Task Performance

The times to complete the manual pegboard task are reported in Figure 6. A 3 X 2 X 10 (type of HMD X HMD order X repetition) mixed, repeated measures analysis of variance was conducted on the dataset of completion times for the pegboard task. By HMD type we mesn: a) no HMD (baseline), b) the see-thru HMD, and c) the control HMD. HMD type significantly affected subjects' time to perform the manual task [F (2, 22) = 102.45, $p < .0001$]. When using the see-thru HMD (Mean = 76 sec.), subjects took an average 43% longer than their baseline performance with no HMD (Mean = 53 sec.) or the control HMD (Mean = 51 sec.) Subjects' performance times improved over the 10 trials. There was no effect for the order in which the subjects used the HMDs [F (1, 11) = 1.21, $p = .21$].

4.2. Effect of See-Thru HMD Usage on Hand-Eye Coordination

Figure 7 shows the amount of error subjects made when pointing at a target without visual feedback of their hand location. The pointing errors are presented for each spatial dimension: (a) X dimension, left-or-right pointing errors; (b) Y dimension, up-or-down pointing errors; and (c) Z dimension, front-or-back pointing errors. The first value in each graph (Figures 7a,b,c) is the baseline value. This value was obtained at the beginning of the experiment when the subjects had not yet put on *any HMD*. This is followed by bars for pointing errors when the subjects wore the control HMD and see-thru HMD. In some dimensions there was a significant effect when subjects used the control HMD either *before or after* the see-thru HMD. In the graphs the control HMD data are shown for both orders of HMD use. As evidence of some adaptation, bars are plotted to show differences in error levels before and after the subjects completed the manual task (pretest versus posttest).

A 2 X 2 X 3 X 5 (type of HMD X HMD order X measurement stage X repetition) mixed, repeated measures analysis of covariance was conducted. The measurement stages were: a) to before conducting the pegboard task, b) after the task, and c) after removing the HMD. The covariate was baseline pointing error (no HMD). The between subjects factor was order of HMD use. The dependent variable was pointing accuracy along each of the three spatial dimensions. Separate analyses were conducted for errors along the X, Y, and Z dimensions.

Pointing Errors Along the X Dimension (left-right of target) See Figure 7a. Although errors appear slightly higher when subjects used the control HMD, type of HMD had no effect on subjects' ability to point accurately on a target along the X dimension [F (1, 11) = .98, $p = .35$]. Effects for order of HMD usage [F (1, 11) = 1.83, $p = .20$] and measurement stage [F (2, 22) = 1.01, $p = .38$] are not significant.

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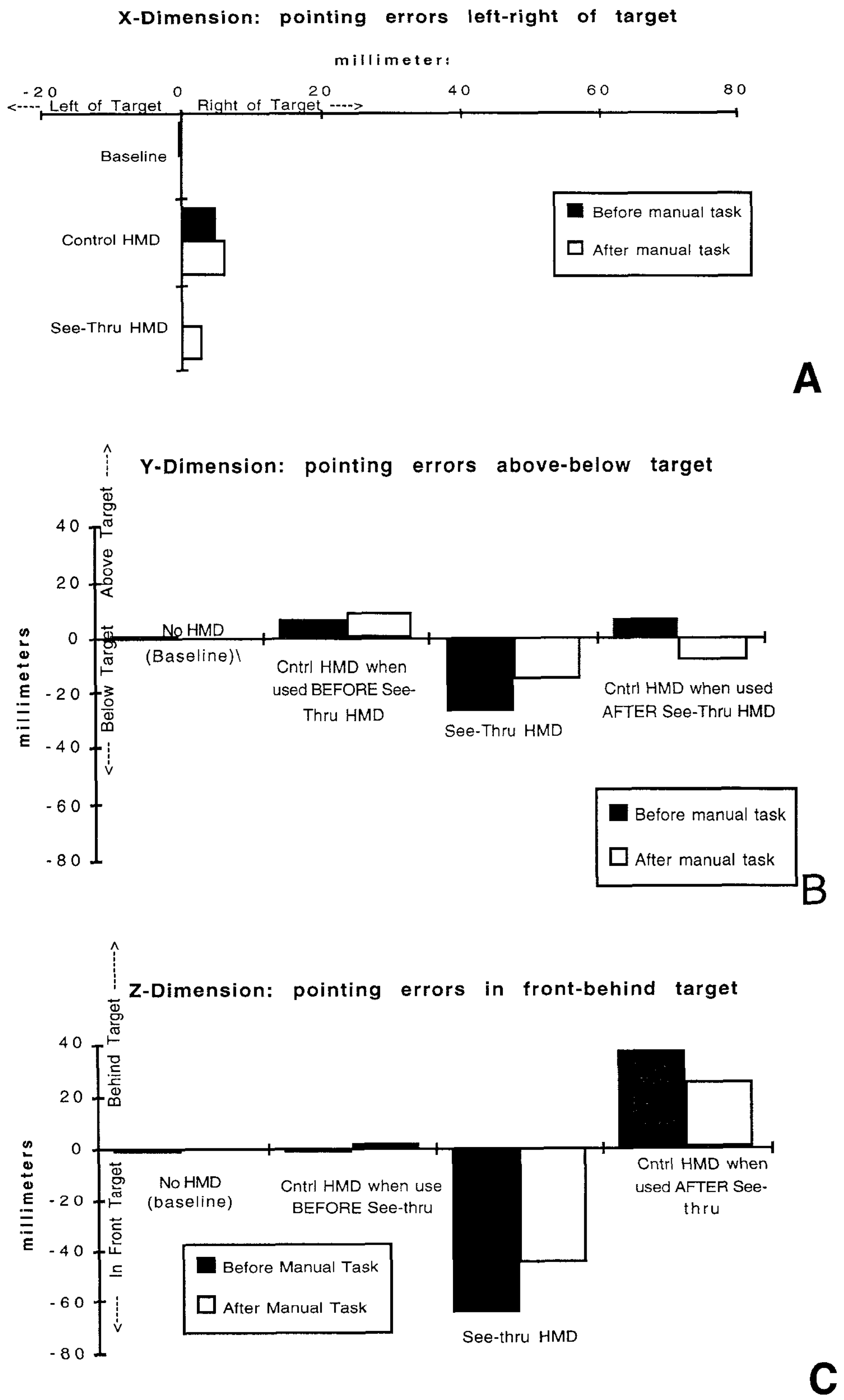

Figure 7. Effect of HMD Type on Pointing Errors By Spatial Dimension.

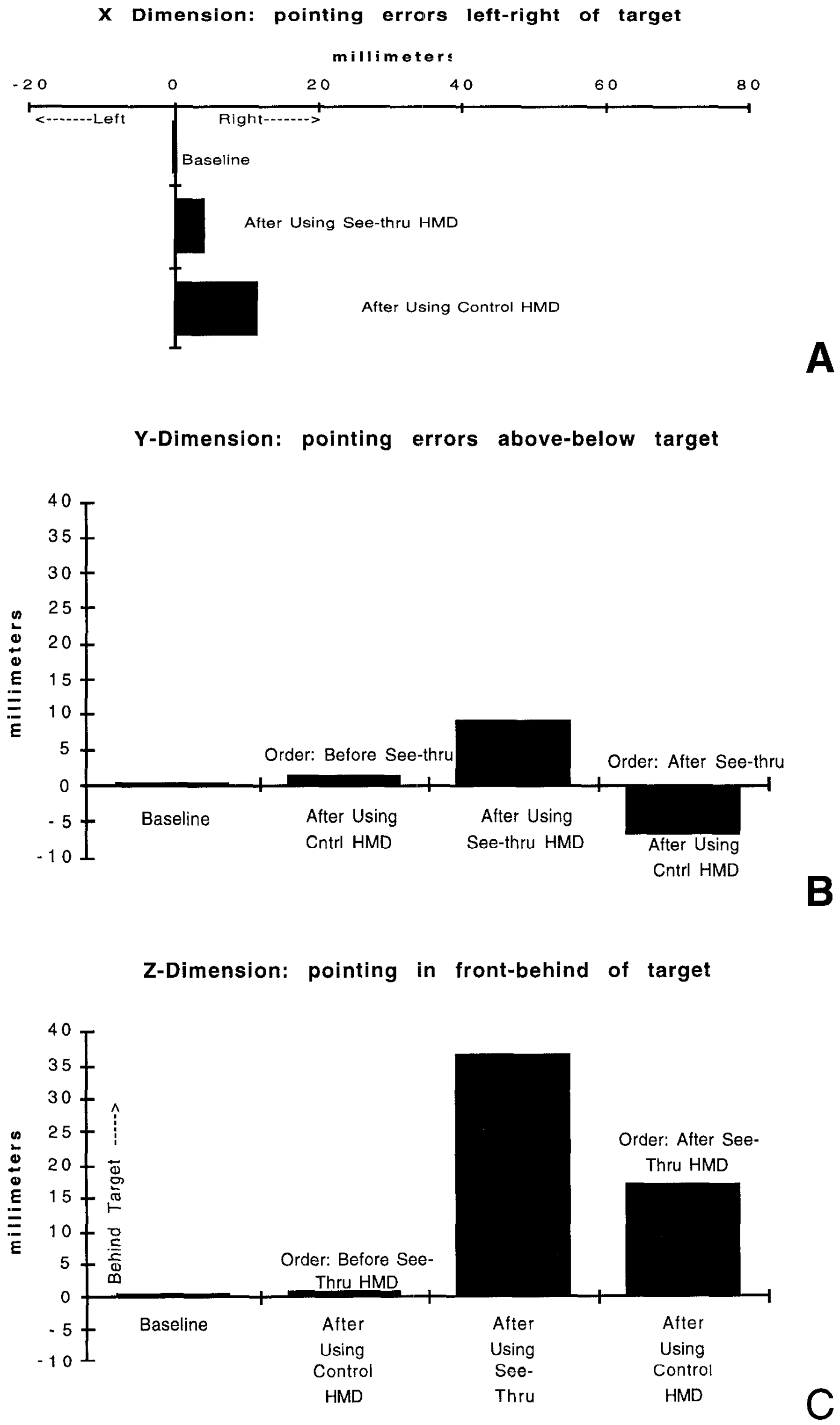

Figure 8. Aftereffect of HMD Type on Pointing Errors by Spatial Dimension.

Pointing Errors Along the Y Dimension (up-down of target). There was a significant main effect for type of HMD on pointing accuracy along the Y dimension [F (1, 11) = 9.77, $p < .01$] See Figure 7b. When subjects were wearing the see-thru HMD that displaced their vision upwards, they tended to point downward of the actual target position. There also was a main effect of measurement stage [F (2, 22) = 8.21, $p < .002$] as well as an interaction of type of HMD by measurement stage [F (2, 22) = 30.85, $p < .0001$]. Subjects' errors tended to decrease following their completion of the manual task while wearing a HMD, but this adaptation effect appears restricted to usage of the see-thru HMD.

Pointing Errors Along the Z Dimension (front-back of target). See Figure 7c. There was a significant main effect of type of HMD on pointing accuracy along the Z dimension [F (1, 7) = 63.29, $p < .0001$]. When subjects wore the see-thru HMD that displaced their vision forward, they tended to point short of the target. There was a main effect of measurement stage [F (2, 14) = 174.76, $p < .0001$]. Subjects' errors were less pronounced after they conducted a manual task using the HMD. Although there was no main effect for the order of HMD usage [F (1, 7) = 1.35, $p < .28$], there was an interaction of measurement stage and order [F (2, 14) = 4.92, $p < .03$]. as well as an interaction of type of HMD by measurement stage [F (2, 22) = 28.25, $p < .001$]. There appears to be no effect when the control HMD preceded use of a see-thru HMD. When the control HMD was used after, there appears to be an effect on pointing error. This may be due to residual after-effects from the see-thru HMD. See below and discussion.

4.3. HMD Use And Negative Aftereffects On Hand-Eye Coordination

The presence of negative aftereffects is commonly used as one of the more telling indicators of adaptation [16]. Figure 8 compares pointing accuracy at four times when subjects are wearing *no* HMD. After subjects removed the see-thru HMD, they displayed evidence of negative aftereffects in their hand-eye pointing accuracy as compared to their baseline performance. The different values of the control HMD along the Y and Z dimension indicate the presence of the order effects reported above. Subjects had the highest level of aftereffects following usage of the see-thru HMD. The aftereffects appear to persist and are still present when the subject uses the control HMD, but only when the latter follows use of the see-thru HMD.

5. DISCUSSION

The see-thru HMD appeared to have a significant effect on the visuo-motor system. Subjects' motor performance decreased. There was evidence that subjects' visuo-motor systems attempted to adapt to the display: (1) initial pointing errors decreased as subjects adapted during the manual task and, (2) they displayed significant aftereffects when they removed the see-thru HMD.

5.1. Effects Of Video See-Thru HMDs On Manual Performance

This study was designed to test the short-term human factors costs of visual displacement typical of large FOV, video see-thru HMDs. The see-thru HMD in this study displaced the subject's eyes to a virtual eye position, 165 mm forward and 62 mm up. The study found pronounced decrement in human performance with this generation of video see-thru HMDs. Performance on a manual task requiring hand-eye coordination took 43% longer with the see-thru HMD.

This drop in human performance appeared to be caused by intersensory conflict between the visual system and the kinesthetic system. After the subjects put on the see-thru HMD, their hand motions were uncertain and tentative. With their altered eye position pushed forward, subjects significantly overshot the pegboard as well as the peg holes in the initial trials. Errors stabilized near the end of the 10 trials as can be seen in Figure 6. Previous research on adaptation suggests that with continued practice the subjects could have performed at speeds close to their baseline speeds. But the lines in Figure 6 are somewhat parallel suggesting that movement towards baseline performance might take quite a few rounds of extended practice. But even with adaptation to visual displacement, the poorer resolution and the more limited field of view of the see-thru HMD may prevent subject performance from reaching performance levels exhibited normally without the HMD.

5.2. The Effect Of Video See-Thru HMDs On Hand-Eye Coordination While Using An Augmented Reality System

The discoordination of visual space and kinesthetic space appeared to be the cause of the drop in human performance. The presence of the discoordination is reflected in the data showing pointing errors. Subjects could not accurately point at objects that they saw because their eyes and hands were discoordinated by the visual displacement of the see-thru HMD.

As expected, the pointing errors were greatest along the spatial dimensions displaced by the see-thru HMD: the Y and Z spatial dimensions. The errors were systematic. Because their virtual eye position was moved up, subjects failed to compensate and pointed lower than the target before they had time to adapt. With their virtual-eye position also pushed forward, they under reached for objects

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before adaptation. Errors, which were on average low at baseline, increased by several 100% after putting on the see-thru HMD. The amount of error dropped by about 1/3 as subjects began to adapt to the sensory rearrangement and would have probably dropped further over longer periods of time.

5.3. The Problem Of Negative Aftereffects Once the HMD is Removed

In the previous section, there was some good news: subjects began to adapt to the visual displacement of the see-thru HMD. This is a positive note for designers of video see-thru HMDs. Humans can adapt to imperfections in see-thru HMDs. But there may be a cost. Unfortunately, this positive change in the virtual environment is linked to a negative change in the real world: there are significant negative aftereffects when the subjects remove the see-thru HMD. The subjects' brains automatically recalibrated the visuo-motor system to meet the altered spatial dimensions of the virtual environment. The virtual-eye location led them to automatically rearrange their body (visuo-motor system). The visuo-motor system was still calibrated for the virtual environment once the see-thru HMD was removed. Subjects found this adaptation interfered with their performance in the "real" world. The HMD removed, subjects exhibited a negative aftereffect, overshooting the target in the pointing task in a direction opposite of the errors they made when they "entered" the virtual environment.

The presence of negative aftereffects has some potentially disturbing practical implications for the diffusion of see-thru HMDs. Surgeons and other medical professionals are the intended early users of these HMDs. Hand-eye sensory recalibration for highly skilled users like surgeons could have potentially disturbing consequences if the surgeon were to perform surgery within some period after use of a HMD.

How long might the negative aftereffects persist? It is an empirical question. In this experiment the effect of the see-thru HMD lasted long enough to disrupt the performance of those subjects who wore the control HMD after the see-thru HMD. Effects might be minimized by a program of gradual adaptation [21] in which users develop dual adaptation [23] to the real and virtual environment. Like scuba divers, users might be able to switch from one environment to another and quickly readapt.

5.4. Some Limitations Of The Study

Although our control HMD was able to match the weight, field of view and discomfort of the see-thru HMD, we were not able to control for the poorer resolution of the unit. Some of the effect on task performance times may be attributable to poor visual resolution, although all subjects said they could definitely see the holes on the pegboard. The actual light conditions in the real world were kept the same in all conditions. But some subjects reported that their hand was casting a shadow on the pegboard when placing the pegs, a shadow that seemed to only affect them while wearing the video see-thru HMD. While poor resolution or lighting effects might have contributed slightly to the poorer performance on the pegboard task, it is highly unlikely that poorer resolution of the see-thru HMD or lighting effects contributed in any significant way to the strong displacement in pointing observed in the subjects.

6. CONCLUSION

Adaptation studies have shown that the human perceptual system is relatively plastic [22]. Faced with most altered perceptual environments, users can adapt partially, if not always fully. The future use of immersive virtual environments in training and entertainment may rest on: 1) this amazing ability of the human perceptual system to adapt to altered environments *and* 2) the creation of VR hardware/software that minimizes sources of intersensory conflict. It is an empirical and practical question whether the present generation of immersive and see-thru virtual environments will provoke levels of intersensory conflict that limit the extent of their utility. While trying to engineer the technology to overcome its limitations, a parallel effort might focus on understanding how well users can adapt to the limitations of the systems [e.g., 21]. Because VE technology will not be able to produce a seamless sensory "reality" for decades to come, research on the adaptive power of the human user is likely to be of continued value in the foreseeable future.

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