The Importance of Accurate VR Head Registration on Skilled Motor Performance

David W. Sprague Barry A. Po Kellogg S. Booth

Department of Computer Science
University of British Columbia
{dsprague, po, ksbooth}@cs.ubc.ca

ABSTRACT

Many *virtual reality* (VR) researchers consider exact *head registration* (HR) and an exact multi-sensory alignment between real world and virtual objects to be a critical factor for effective motor performance in VR. Calibration procedures, however, can be error prone, time consuming and sometimes impractical to perform. To better understand the relationship between head registration and fine motor performance, we conducted a series of reciprocal tapping tasks under four conditions: real world tapping, VR with correct HR, VR with mildly perturbed HR, and VR with highly perturbed HR. As might be expected, VR performance was worse than real world performance. There was no effect of HR perturbation on motor performance in the tapping tasks. We believe that sensorimotor adaptation enabled subjects to perform equally well in the three VR conditions despite the incorrect head registration in two of the conditions. This suggests that exact head registration may not be as critically important as previously thought, and that extensive per-user calibration procedures may not be necessary for some VR tasks.

CR Categories: H.1.2 [User/Machine Systems]: Human Factors—Human Information Processing; H.5.1 [Multimedia Information Systems]: Artificial, Augmented, and Virtual Realities—Evaluation/Methodology

Keywords: virtual reality, head registration, calibration, motor ability, tapping tasks, sensorimotor adaptation

1 INTRODUCTION

Realistic head-coupled perspectives in an immersive *virtual reality* (VR) environment require precise calculations and measurements. Deering's work on high resolution VR clearly demonstrates the benefits that precise measurements and attention to calibration detail have on motor ability in VR [7]. The impact that each VR factor has on the user, however, is not immediately apparent. Parameters such as field of view, system lag, and scene lighting have varying importance for a particular task. Ensuring that each VR parameter is correct takes time, so cost/benefit tradeo-ffs arise, especially when some calibrations are difficult or impractical to perform. Our research investigates the importance of *head registration* (HR) accuracy on motor performance in a *virtual environment* (VE).

We define *registration* as the procedure of aligning and synchronizing sensory elements, either within one sense or across sensory modalities [3]. In our experiment we register the position of a real world tapping board (described later) with its corresponding VR representation so that tactile, auditory, and visual representations of the virtual board align with the real object (Figure 1). Head registration is the measurement of a subject's head and eye positions and the position and dimensions of the HMD's view screens relative to a tracked object in order to present a realistic head-coupled perspective of the VE. The most accurate HR we can accomplish using our calibration methodology will be referred to as *optimal head registration* (OR). The *display field of view* (DFOV) is currently defined the subtended angle from the subject's eye to the edges of an HMD view screen [6]. The *geometric field of view* (GFOV) is defined as the subtended angle from the virtual camera to the edges of the image plane. This relates to how much of a virtual scene can be observed from a given VR camera perspective. If head registration is ideal, horizontal and vertical GFOVs are equivalent to the corresponding DFOVs. Perturbing HR during the experiment increased the GFOVs while DFOV values were constant.

It is important to investigate how incorrect registration affects VR use because exact HR can be difficult to perform, error prone, and problematic to maintain. *Head-mounted displays* (HMD) can shift during head movements and the focal center of the human eye can be difficult to precisely locate [7]. Despite this difficulty, many VR researchers claim that HR registration is critical for an effective VR system [2, 8, 32]. In order to examine the effects of HR quality on performance we need a registration methodology, an appropriate environment in which to test subjects, and a theory on which to base our research. We discuss each of these and then describe our experiment and results.

1.1 Head and Eye Measurement Techniques

Optimal HR for an HMD requires an accurate method for determining tracked object to eye and tracked object to view screen vectors. Surprisingly, there are few published methodologies for HR in immersive virtual reality using an HMD. Stevenson's [24] fish tank VR head registration technique uses the screw holes in two magnetic tracking sensors and a third magnetic tracker attached to the head to extrapolate line of sight information. Subjects aligned the screw holes of two sensors along their eye's gaze direction so a far away object could be observed. Taking sensor position information for several sensor alignments allowed the software to determine the first nodal point (focal point) of the subject's eye relative to the head sensor. Tracker signal noise requires best fit approximations to be used, and this technique was not sufficiently precise for the registration we required. There are HR techniques for augmented reality (AR) displays and VR tables, but they rely on subjects aligning real world and virtual objects [3, 25]. An HMD obscures the real world, so these techniques cannot be used. Therefore, we developed a new HR technique for this experiment.

1.2 Passive Haptic Feedback in VR

To measure the effects of errors in HR on VR motor performance, we used *passive haptic feedback* (PHF), where correct registration is deemed crucial in previous literature [1, 28]. Passive haptic feedback in VR is proprioceptive (knowledge of the body's position and orientation) and tactile information provided to the user through interactions with a real world object or input device.

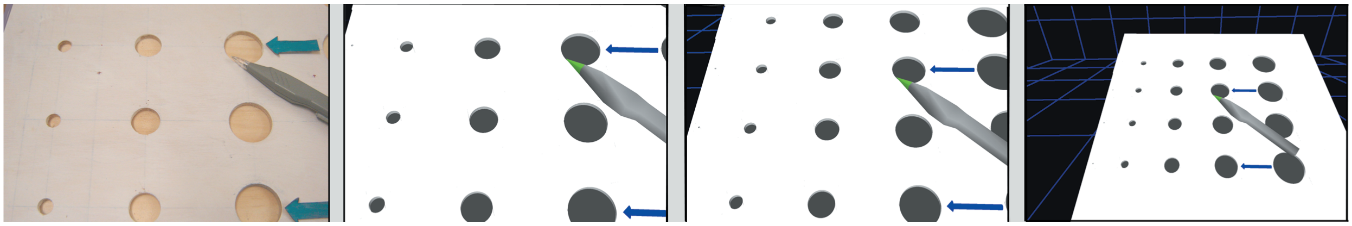

Figure 1: The effects of head registration accuracy on virtual reality visuals when subject head position is static. Images from left to right: the real world tapping board (RW), VR in the optimal head registration condition (OR), VR with a small registration error (MR), and VR with a large registration error (WR).

PHF has been shown to enhance a user's sense of presence and improve motor task abilities [1, 4, 27]. Multisensory information such as PHF requires object registration to ensure sensory correspondence (when you see a tap, you feel a tap). Some researchers suggest a need for a *"What you see is what you feel"* or *WYSIWYF* approach to VR haptic design. Yokokohji et al. [32] suggest that an exact correspondence between the various sensory modalities is required. If an object being manipulated is directly in front of the subject, proprioception should indicate that the object is in exactly that location. WYSIWYF requires HR to be as precise as possible to ensure that the same haptic/visual correspondence achieved in the real world is provided in VR. Wang and C. MacKenzie's [26] work on haptic/visual size correspondence identifies movement time as dependent on real and virtual object correspondence. In a VR object alignment task, virtual objects co-located with a matching real world object performed significantly better than an alignment task without real and virtual objects being co-located [30]. Ware and Arsenault [28] found that the degree of axis mis-alignment between the subject's frame of reference and prop object's frame of reference was associated with a quadratic increase in movement time, further supporting the need for accurate HR.

1.3 Sensorimotor Plasticity/Adaptation

Experiments using prism glasses have shown that the correspondence between motor functions and the senses is dynamic and constantly recalibrating [13]. Subjects can adapt to a variety of alterations to their vision so that after repeated self-produced movements the subject can function normally in the altered state [13, 19]. This adjustment to systematic sensory alterations is known as *sensorimotor adaptation* or *sensorimotor plasticity*. When the disturbance is removed, temporary movement errors in the opposite direction of the alteration are observed. This is known as a *negative aftereffect* [13].

Previous research suggests that sensorimotor plasticity occurs in virtual and augmented reality as well as in the real world. Ellis et al.'s [9] immersive VR visual tracking experiment with control display misalignment clearly demonstrated a training or sensorimotor adaptation effect as relative error rates in misaligned conditions approached the perfect alignment scores over time. Adaptation has been seen in video-based *augmented reality* (AR). Video-based AR alters a user's perspective of the real world, but subjects showed performance improvements in their pointing accuracy with prolonged exposure to the system, and a negative aftereffect was demonstrated when subjects removed the AR display [20]. Groen and Werkhoven [12] demonstrated that sensorimotor adaptation occurs in virtual reality as well. They found real world negative aftereffects when they displaced a subject's hand representation by a small amount in VR, but no significant performance differences between the misaligned and the correctly aligned VR hand positions. Our research investigated how readily sensorimotor adaptation occurs with passive haptic feedback, following the approach of Groen and Werkhoven. We examined a range of systematic registration errors to study how perturbation magnitude affects motor performance. For more details about the current experiment, see work by Sprague [23].

2 HYPOTHESES

Based on previous experimental work, we believe that head registration may not be as critically important as previous VR literature suggests, and that sensorimotor adaptation allows people to compensate for incorrect HR. We devised an experiment with four different viewing conditions (Figure 1): *real world* (*RW*), VR with *optimal HR* (*OR*), VR with *moderately perturbed HR* (*MR*) and VR with *highly perturbed (worst) HR* (*WR*). We tested the following experimental hypotheses:

H1 There will be significantly slower movement times and a greater error rate in the three VR conditions compared to the RW condition because VR elements such as FOV, lighting, and lag result in fine motor performance in virtual reality being slower and more error prone than the same motor task performed in the real world.

H2 Movement times and tapping accuracy in the WR condition will be slower and more error prone than performance in the other two VR conditions. There will be no movement time or accuracy differences between OR and MR conditions because small perturbations can be adapted to quickly. Extremely incorrect HR will take longer to adapt to, so a motor performance decrease will be observed.

H3 Movement time will decrease and accuracy scores increase with time (trial number) during each experimental viewing condition because of sensorimotor adaptation. We theorize that subject movements will be negatively affected by changes in HR, but this performance decrease will disappear as subjects adapt to the new visual, tactile, and motor associations. Performance will not improve with condition number. Practice prior to the experiment should minimize cross condition learning effects.

3 EXPERIMENTAL DESIGN

The experiment consisted of four main phases: screening, head registration, practice trials, and experimental trials. A 4 (viewing condition) × 3 (target distance) × 4 (target width) within subjects design was used. The experiment required subjects to move a magnetically tracked stylus back and forth between two target holes (a *target pair*), attempting to successively place the stylus in each hole as quickly and accurately as possible (each placement is an *experimental trial*). Each of the 12 target pairs involved a minimum of 25 tapping trials (*a block*) with each subject completing 1200 trials over all conditions.

3.1 Subjects

Twenty-four subjects (13 female, 11 male) ages 18-28 were recruited from a university undergraduate and graduate population. Viewing condition order was fully counterbalanced across subjects. All subjects were right handed, had normal or corrected to normal vision, and tested positive for gross binocular vision (in particular, for stereopsis) using the Titmus Stereo Fly test [17]. No subject had more than 2 previous immersive VR experiences and all subjects used a computer daily. Each experimental session took approximately one hour. Subjects were financially compensated for their time.

3.2 Equipment

Subject eye measurements were made using a pinhole headband, shown in Figure 2. The pinhole headband consists of pairs of orthogonal bolts connected to each other via two bonded nuts. The horizontal bolt is loosely attached to a metal frame so that it can rotate without translating. This means that the nut threaded on this bolt moves left or right as the bolt turns. The vertical bolt indirectly connected to this nut is free to translate up and down when rotated. The metal frame is attached to a simple adjustable headband worn by the subject. An eye cover with a pinhole is attached to each vertical bolt. In this way, the covers blocking a subject's view can be precisely moved with two degrees of freedom. The pinhole headband was adjusted until subjects were able to see an object four meters away, through the pinholes. Measuring the distance from the headband to each pinhole and the distance between the pinholes allows us to calculate the location and separation of a subject's eyes. The estimated measurement resolution using the pinhole headband is approximately 3mm.

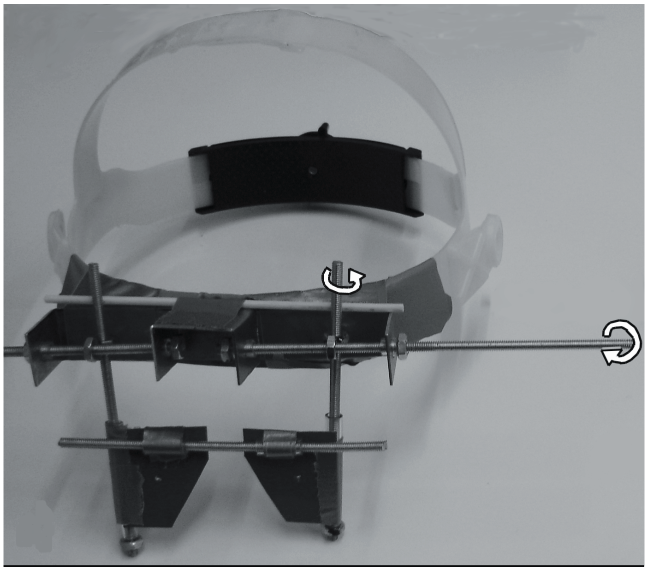

Figure 2: The pinhole headband used to measure eye location and interocular distance. Arrows indicate how the adjustment bolts operate.

3.2.1 Tapping Board

A 457mm × 457mm wooden board was used as the tapping surface (Figure 3). The board's surface was inclined at a 30 degree angle from horizontal to reduce subject neck strain. The top of the board was painted white. The structure was securely attached to a wooden experiment table 74 cm from the ground. No metal was within one meter of the board's surface. All holes were 0.3mm deep.

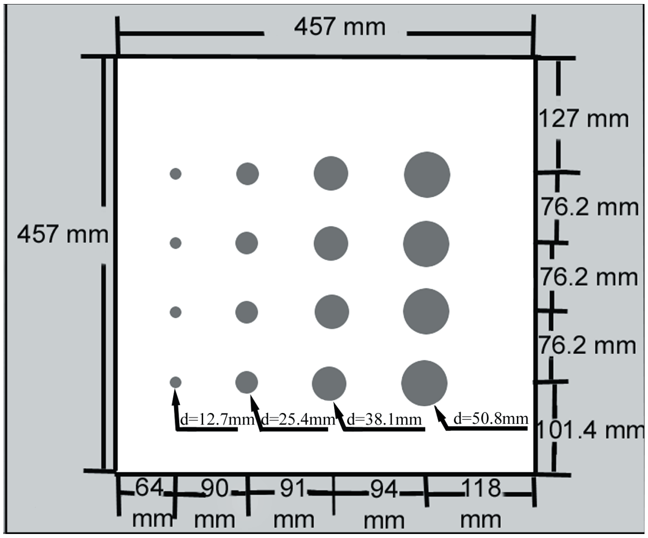

Figure 3: The experimental tapping board.

3.2.2 Magnetic Tracker

A 6 degree of freedom Polhemus Fastrak magnetic tracker monitored subject movements during the experiment using an HMD mounted sensor for head tracking, and a stylus pen for tapping [18]. A VR representation of the stylus was seen in the VR conditions, which matched the real object's position and orientation relative to the tapping board (Figure 1). The Fastrak receiver was attached below the tapping board on the far left side providing maximum precision and accuracy for the smallest target holes. Each Fastrak sensor was sampled at 60Hz by a separate processing thread in the VR program. This ensured that the sampling rate was independent of the update rate.

The location and orientation of the tapping board was calculated in advance by sampling the stylus as it touched 6 predefined board locations. The surface normal of the board was then confirmed by taking a large (100+) sample of surface points. In VR, the experimenter moved the stylus around the inside circumference of each VR tapping hole, noting any times the stylus intersected the tapping board. This confirmed tapping board and VR image registration to be less than 2mm on the left side of the board and within 3mm on the right side. Precision is limited by the 1mm resolution of the Fastrak sensors. Registration was confirmed before each experimental session.

3.2.3 Head Mounted Display & Virtual Environment

A Kaiser ProView XL50 head mounted display with a 1024×768 resolution, 40° (horizontal) × 30° (vertical) display field of view and dual input video channels (one for each view screen) was used in the experiment [15]. The HMD weighed approximately 1 kilogram. The HMD optical modules were opened to measure the size and position of each view screen. The screen locations were then marked on the outside of each eyepiece to simplify adjustments and measurements. The HMD permits subjects to wear glasses if required. A large piece of black cloth was sewn onto the HMD and placed in front of the subject's face to remove real world peripheral information and to reduce light glare on the HMD optics. Video signals to the HMD were split and displayed to the experimenter on two private monitors. This allowed the experimenter to monitor subject behavior.

A 3 GHz dual CPU Linux machine with 1GB of memory, and an nVIDIA Quadro4 980 video card (128MB RAM with dual video out) was used to create the virtual environment using OpenGL. The average frame rate was 45 frames per second. System lag was estimated to be 60ms [29]. The VE displayed representations of the tapping board and the tapping stylus manipulated by subjects. Figure 1 shows the physical tapping board as a subject would see it in the RW condition, and the virtual images that would be seen in each of the three VR conditions for the same head location and orientation. The tip of the VR stylus was coloured green and the bottom of the tapping board was coloured black to enhance visibility and depth perception in VR based on pilot subject feedback. VR objects were not textured and did not produce shadows.

3.3 Procedure

Subjects signed a consent form at the start of the experiment provided they matched our criteria and tested positive for stereopsis using the Titmus Stereo Fly Test [17, 21]. VR experience and frequency of computer use data were collected at this time.

3.3.1 Eye Measurement and HMD Adjustment

Subjects were asked to put on the HMD and adjust it so that it felt comfortable and secure on their head. Subjects placed a finger on their forehead just below the HMD's headband. The HMD was removed and a small piece of electrical tape was placed where their finger was located. This provided a point of reference for aligning the pinhole headband and the HMD. HMD and pinhole headband positions were estimated to be within 4mm of each other using this technique.

The pinhole headband was placed on the subject's head just above the tape reference. The experimenter, with the subject's verbal feedback, adjusted each eye cover until the participant could view the light switch on the far wall of the room through the two pinholes. The HMD was adjusted based on the pinhole headband measurements, and placed back on the subject's head. The distance from the view screen (marked on the HMD) to the first nodal point of the subject's eye was then measured using a ruler [7, 24]. The first nodal point of a subject's eye was approximated to be 8mm in from the cornea and we estimate this measure to be accurate to within 3mm (Figure 4).

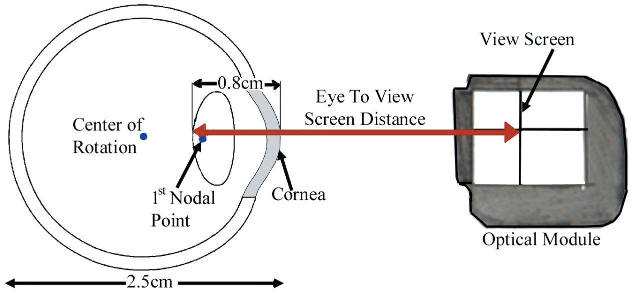

Figure 4: Measured distance from an HMD view screen to the estimated first nodal point of the subject's eye.

For optimal HR, each image plane in the VR scene was the same size and position as a view screen of the HMD. Each of the subject's eyes corresponded with a VR scene's virtual camera. Eye positions relative to the head tracking sensor were calculated by measuring the distance from the sensor to the HMD headband and the distance from the headband to the subject's eyes (using the pinhole headband). Sensor to view screen vectors for all HMD adjustments were discerned prior to the study. A series of affine transformations then transformed the real world tracker information into VR camera and image plane position and orientation information, providing an optimal head-coupled perspective of the virtual world.

3.3.2 The Tapping Task

For this experiment we used a Fitts-like reciprocal tapping task because it is a well defined, well documented, and well understood motor activity [22]. Seated subjects were asked to repeatedly tap forward and back between two target holes of the same diameter using the stylus until instructed to stop by the experimenter (Figure 5). A tapping event occurred when either the stylus entered a hole, or came in contact with the top of the tapping board. A polygon collision algorithm determined when the stylus contacted the board. The next trial began when the tapping event ceased.

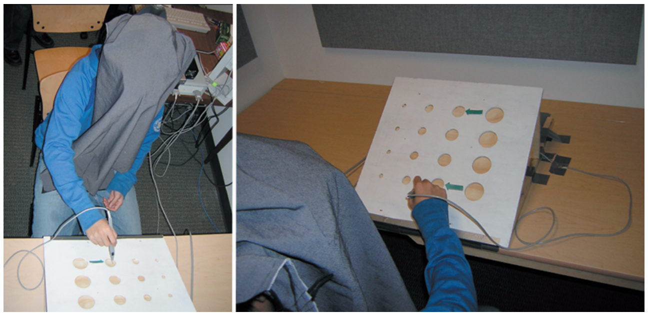

Figure 5: Two perspectives of the reciprocal tapping task being performed during an immersive VR condition.

Subjects were given tapping task instructions and were shown how to perform the reciprocal tapping task. Subjects were told that for each trial they should contact the tapping board with the stylus and they should always aim to hit the center of a target hole, although anywhere in the hole was considered a successful trial. Participants were asked to tap as quickly and accurately as possible. They were told to have approximately a 4% error rate (one error in 25 trials) [22]. Subjects had no trouble understanding the task. The experimenter demonstrated the real world reciprocal tapping task and asked subjects to do the same on a different pair of targets to make sure they understood the instructions. Subjects put on the HMD and performed 30 practice VR trials with optimal HR.

Target pairs were always located in the same column and the bottom hole was always in the row closest to the subject. The top hole was randomly selected from one of the three remaining targets in the column. This provided 12 possible target pair combinations and 9 distinct index of difficulty (ID) values ranging from 1.32 to 4.24. For each block of target pair trials, blue arrows on the board identified the two target holes (Figure 1). For each target pair, subjects were asked to tap until instructed to stop by the experimenter. The first 4 tapping trials were not used as they were deemed additional practice trials. The trial data was recorded to a text file for each of the next 21 taps.

Blocks of trials were grouped so that all trials with the same target width were together. Block ordering within this group was randomized. The order of the four groups (columns) was also randomized. When all twelve blocks were completed, the end of the condition was indicated by a black screen. Subjects were given up to a five minute break to take off the HMD (when applicable), relax, stretch and ask questions.

Subjects experienced four viewing conditions: real world tapping, VR tapping with OR, VR tapping with MR, and VR tapping with WR. The three virtual reality conditions required subjects to wear the HMD. Arrows indicating the target holes were automatically displayed in the VR scene when each block of trials began.

The distance between the VR camera and the image plane was adjusted to match the distance from the subject's eyes to the view screen in the real world. Reducing the distance between the camera and the image plane thus perturbed head registration and increased the GFOV. The three VR conditions differed exclusively in how a subject's head registration was perturbed. The image plane in the MR condition was 0.5cm closer to the camera than in the optimal condition and 2.0cm closer to the camera in the WR condition (Figure 6). Camera to the image plane perturbation was used because the view screen-to-eye distance was deemed the most difficult and most error prone measurement to make, hence the most likely source of registration error.

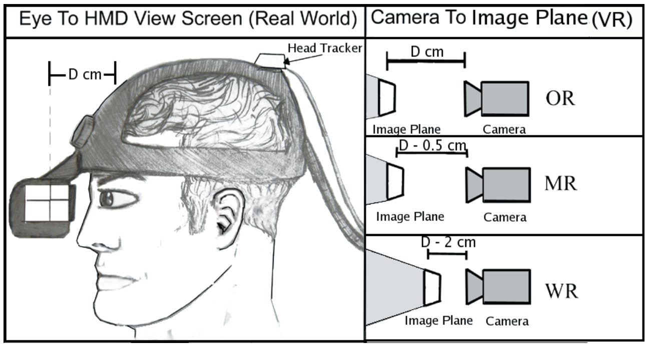

Figure 6: The real world/virtual reality correspondence between the eye to view screen distance (D) and the camera to image plane distance in each VR condition. The eye to view screen distance ranged from 4.3 cm to 6.3cm with a mean of 5.61cm.

The real world condition did not require any headgear to be worn. Coloured cardboard arrows were positioned on the tapping board by the experimenter before each group of pair trials began. The number of trials remaining, and the target holes to tap were displayed to the experimenter via private monitors.

4 RESULTS

To determine what impact registration quality has on fine motor performance, we looked at primary measures of movement time, task correctness and information processing throughput. Movement time is the interval from the start of a tapping trial to the end of the trial (when a tap occurs). Task correctness was measured in two ways: root-mean-square (RMS) distance from the target center, and percent of trials tapped successfully (percent correct). The RMS distance from the target center is the distance between the stylus's intersection point and the target hole's center. Percentage correct refers to the percentage of included trials that were successful in a given trial pair. We calculated information processing throughput values according to S. MacKenzie's formula [22]. This metric provides a general measure of tapping ability for each of our experimental conditions.

We used a factorial analysis of variance with repeated measures (ANOVA-RM) over three independent factors: experimental condition, trial pair order, and condition order. A one-way between subjects ANOVA was used to investigate how subject-specific factors affected the dependent measures. Subject data was coalesced for each experimental condition, and a test of correlation and linear regression between index of difficulty (ID) and movement time was performed. ID was calculated using the Shannon formulation [22]. From these linear regressions, slopes, y-intercepts, and R^2 adjusted correlation coefficients were examined (Figure 7).

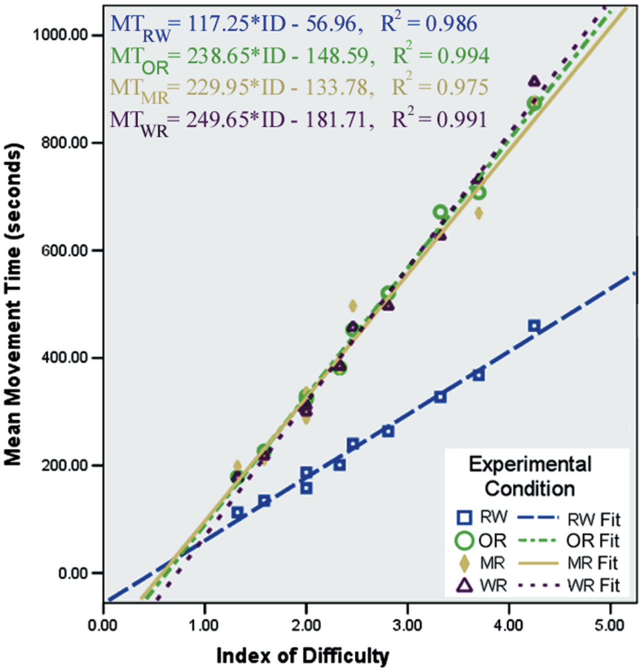

Figure 7: The correlation between index of difficulty and trial movement times for real world (RW), optimal VR registration (OR), moderate VR registration (MR), and worst VR registration (WR).

4.1 Data Cleaning

When subject data was initially examined, extreme outlying data points were quickly apparent. For a given target pair, any trials more than three standard deviations from the mean movement time were removed. Because we wanted to examine stable performance times, we tested for a performance plateau during a block of trials. A plateau was identified when 3 consecutive trial times did not improve by more than 600 milliseconds. All trials before a plateau were removed. If performance did not plateau, then the final trial of the group was used. In the 1152 blocks of trials collected, 5 did not plateau (with a maximum of 2 from one subject) and 1118 blocks had 0 or 1 trials dropped. Average trial drop rates were highest with high ID blocks (2.104 for ID = 4.25 and 0.073 for ID = 1.32). Less than 4% of trials (0.84 trials per block of 21 trials) were removed from a viewing condition. The overall mean number of removed trials was 0.431 trials per block with a standard deviation of 2.12.

4.2 Linear Regression and Fitts' Law

Tapping trials in all four conditions followed a Fitts' law linear regression pattern as expected. All linear regressions had R^2 adjusted coefficients greater than 0.97 and all y-intercept values were greater than -200 milliseconds (Figure 7) [22]. Data was also tested using

Welford's model and Fitts' original formulation, but the Shannon formulation showed better R^2 correlation coefficients than these other mathematical models. Thus, all data analysis reported in this paper used the Shannon formulation. Error rates for subjects were all less than 4% after data cleaning, which is consistent with how subjects were asked to perform.

4.3 Virtual Reality vs. The Real World

Our primary repeated measures ANOVA found a statistically significant difference between viewing conditions in terms of movement times $[F(3,21) = 43.5, p < .001]$, percent correct $[F(3,21) = 8.4, p < .001]$, and the RMS distance to the target center for top targets $[F(3,21) = 10.4, p < .001]$ and bottom targets $[F(3,21) = 12.6, p < .001]$. Mean metric values for each condition can be seen in Table 1.

Table 1: The mean movement time, error rate (% of kept samples), % of trials dropped, and information processing throughput based on experimental conditions.

Condition	Movement Time (ms)	Root-Mean-Square Variance (cm)	Error Rate (%)	Trials Dropped (%)	Information Processing Throughput
RW	248	0.455	0.12	0.1	0.0160
OR	473	0.554	1.50	3.5	0.00866
MR	466	0.522	0.62	1.7	0.00880
WR	466	0.534	1.50	2.9	0.00888

A repeated measures ANOVA found no significant differences between the VR viewing conditions in terms of movement time or percent correct. A partial Eta-squared test for effect size was 0.046 for the effect of VR condition on movement time. To put this into context, a partial Eta-square value of .01 indicates a small effect, .06 indicates a medium effect size, and a partial Eta-squared value of .14 is a large effect size [5]. Cohen argues that a lack of significance, a small partial Eta-squared effect size and low variability data indicates little to no effect of a condition. Our results suggest that HR perturbation has no effect on subjects performing a Fitts-like reciprocal tapping task [5].

4.4 Ordering Effects

Subjects showed a significant movement time improvement based on trial pair number within an experimental condition with the mean first pair's time being 0.511ms and the twelfth pair's mean time equaling 0.349ms $[F(11,13) = 4.8, p < .05]$. There was no significant effect of time on task correctness, nor were there any significant effects of condition order on movement time or task correctness. These results suggest that subject performance improves with exposure to an experimental condition but ordering effects are not seen across conditions. Individual subject differences and index of difficulty variability made estimating sensorimotor adaptation rates unreliable.

4.5 Between Subject Factors

Finally, subject-specific characteristics showed no significant effect on tapping performance. A one-way ANOVA revealed no significant relationship between sex, stereopsis scores, measured eye position, interocular distance, or VR experience with any of the performance metrics.

5 DISCUSSION AND FUTURE WORK

Two main results can be observed from this experiment's data. First, Fitts-like reciprocal tapping in a VE is significantly slower and more error prone than tapping in the real world. This result confirms *H1* and could be due to a combination of factors including: the HMD's weight, system lag, fewer depth cues in VR, the VR frame rate, and image quality [14, 16]. Subjects may have also felt freer to move about without the constraints of the tethered head mounted display [31]. Our results suggest that the differences between VR and the real world are not due to head registration difficulties as previous research suggested [8].

The second result from our experiment is the lack of difference between VR conditions. Cohen's work suggests that our small partial Eta-squared value for the VR condition's effect on movement time indicates that registration quality has little to no influence on motor performance [5]. This result does not agree with *H2*, but it is consistent with sensorimotor plasticity theories. If sensorimotor adaptation is occurring, it happens more rapidly than we expected. The trial performance improvements over time within a condition, but not between conditions (*H3*), are also consistent with a sensorimotor adaptation explanation of our results.

There is a second possible explanation for our failure to observe an effect of VR condition. By moving the image plane closer to the camera, we increase the GFOV. Eggleston et al. [8] found that movement time for a Fitts-like tapping task decreased when the GFOV was increased and targets had a moderate difficulty level. In our experiment, target distances were 7.62cm, 15.24cm, and 22.86cm, and subjects viewing the board from 30cm away could see approximately 17.7cm of the board in the OR condition, 20.4cm in MR, and 37.2cm in WR. Thus, fewer head movements were required as the HR disturbance increased and performance may have improved because of this. The "wide-angle lens" effect of our HR perturbation, however, reduces image clarity and the DFOV no longer matches the GFOV, possibly reducing tapping performance. Hence opposite factors may produce the lack of effect we observed. Nevertheless, either explanation of our results suggests that other virtual reality factors are more important than HR for motor performance in VR.

If precise head registration is not the critical factor for VR, other elements of a VR system should perhaps take a higher priority. If time and money are not constraints, optimal registration and calibration should always be performed to guarantee realistic VR. Sensorimotor adaptation between the real world and virtual world should be avoided to reduce negative aftereffects in real world tasks. However, exact HR is not always possible or practical and it does not seem necessary for quick or informal VR use. Approximate measurements may suffice. A five minute motor task in VR should enable sufficient adaptation. We believe that interocular distance should continue to be precisely measured because it is relatively easy to find, is constant for individual subjects, and correct measurements may reduce eye strain.

Our experiment does not provide us with a clear explanation for HR's lack of effect. Other registration errors should be investigated to ensure our results generalize. Lateral shifts in vision are the most common prism adaptation experiments [12]. Repeating this experiment using a lateral shift instead of a camera/image plane error would mean that the GFOV is not altered. If no significant differences between perturbation amounts are found, the opposing factors explanation would not be supported. Future experiments should also test HR effects on perception, subject preference, and sense of presence in VR.

6 CONCLUSIONS

Our experiment examined the effect of head registration perturbations on motor performance in VR environments. We utilized a low cost, efficient and precise methodology for immersive VR head registration using a pinhole headband. Our results clearly demonstrate that motor performance in an immersive VR system is significantly worse than performance in the real world, and we have provided evidence that perturbing the distance between the camera and the image plane in VR does not affect subject motor performance, even when the perturbation is extreme. We believe that this lack of an effect is due to sensorimotor adaptation, and that subjects are able to adjust to most moderate head registration errors with enough practice. Exact head registration may not be a crucial factor in virtual reality as previous research has suggested.

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