Improving the ergonomics of hand tracking inputs to VR HMD's

Scott Devine
Queen's University Belfast
Northern Ireland
sdevine08@qub.ac.uk

Chris Nicholson
Carleton University
Ottawa, Canada
chrisnicholson@cmail.carleton.ca

Karen Rafferty
Queen's University Belfast
Northern Ireland
K.Rafferty@ee.qub.ac.uk

Chris Herdman
Carleton University
Ottawa, Canada
chrisherdman@cunet.carleton.ca

ABSTRACT

This study improves the ergonomics of using the Leap Motion hand tracking device with an Oculus Rift. The improvements were realised through the use of a 3D printed mount that angled the Leap Motion down by 30 degrees. This allowed for users to interact with a virtual environment in which their arms may be held in a biomechanically less stressful location, rather than up and in front of their face. To validate the configuration, 15 participants completed a specially designed task which involved pressing virtual buttons in a given location. The button pressing task was performed in three configurations that compared the angled mount against the standard forward facing mount. Results indicate that the angled mount eliminates tracking loses, whilst producing comparable accuracy against the control condition and allowing the participant to interact in a more natural arm posture.

Keywords

Human Computer Interaction; Hand Tracking; Virtual Reality; Leap Motion; Oculus Rift;

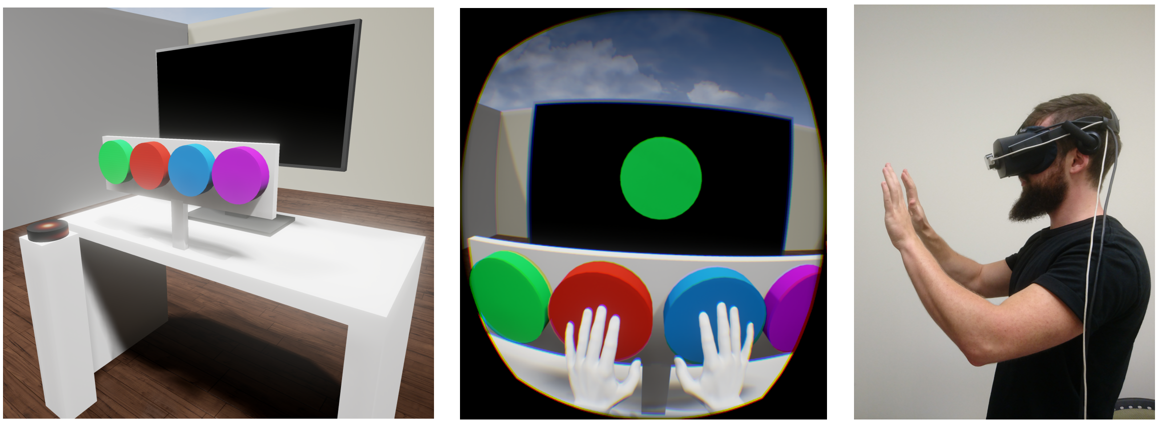
1 INTRODUCTION

In recent years the VR (Virtual Reality) industry has grown considerably with the mainstream adoption and release of multiple high fidelity HMD's (Head Mounted Displays) including the Oculus Rift [1] and the HTC Vive [2]. Both of these HMD's use physical hand controllers that allow users to interact with the virtual environment. These controllers are very accurate, but do not allow for the natural inputs afforded by the entire hand and fingers. An ideal solution would involve high fidelity low latency hand tracking that allows the user to manipulate 3D representations of his/her own hands in VR.

The Leap Motion [3] device was designed to allow users to interact in virtual environments using only their hands. It is an optical tracking device that uses time of flight calculations from emitted infrared light to track both the hands and fingers in 6 DOF. Though originally designed as a desktop mounted device, the potential to solve the limitations of inputs in VR with physical controllers was realised. Leap Motion's Orion update allowed the device to be mounted directly on a HMD and track the hands in front of the face. The Leap's software has undergone serious optimisations whilst the hardware remains the same. The Leap Motion now tracks a participants hands with the highest accuracy with the palms facing away and parallel to the device, this can be seen in Figure 1c.

However, the limited 120 degree horizontal FOV (Field Of View) produces a new set of challenges when tracking users hands in VR. A user has to bring their hands directly into view (Figure 1c) or point the HMD toward what they are interacting with (Figure 2c). Both of these movements are unnatural and have the potential to cause user discomfort. Persistently elevated arm positions in user interfaces causes arm fatigue [4, 5] and looking down at the hands causes discomfort in the shoulders and neck when used for extended periods. Ideally, the FOV of the Leap Motion would be large enough to allow the user to look forward and interact with his/her forearms at a more ergonomic 90 degree to his/her body (Figure 3c).

The research documented within this paper was designed to investigate the potential for an angled mount to mitigate the aforementioned limitation of current Leap Motion design. The mount developed for this research, angles the Leap Motion down, toward the users hands by 30 degrees. This changes the optimal tracking area, allowing a user to look up and forward at the surrounding environment, whilst their hands are still tracked. As shown in Figure 3c this allows users to interact with the environment in a more comfortable manner. It was hypothesized that moving the effective



(a) Scene view of desk and monitor with forward pressing buttons

(b) User view of Forward condition

(c) Interaction posture of Forward condition with original mount

Figure 1: Forward Condition

tracking range down would eliminate tracking loses, improve user comfort and provide a better VR interaction experience. Section 2 details related literature, however, to the knowledge of the authors no one has attempted to angle the Leap Motion whilst attached to a HMD before. Section 3 covers the device and mount set-up and Section 4 details the conducted user study. The results are detailed and discussed in Section 5, with Conclusions in Section 7.

2 RELATED WORK

The Leap Motion has been used for numerous human computer interaction studies from numerical gesture recognition [6] to hands-free immersive image navigation [7]. The Leap Motion has allowed researchers to acquire 6 DOF tracking data of both the hands and finger at millimetre accuracy [8, 9]. Though still using hardware from 2013, the Leap Motion controller continues to under go software revisions, most recently receiving the Orion update. This update was specifically designed to improve use when mounted on VR headsets. However, little research uses the Leap Motion mounted on the front of the HMD, it is instead used in a desktop fashion. Both desktop and HMD mounted configurations of the Leap Motion can cause fatigue and this is reflected in the literature.

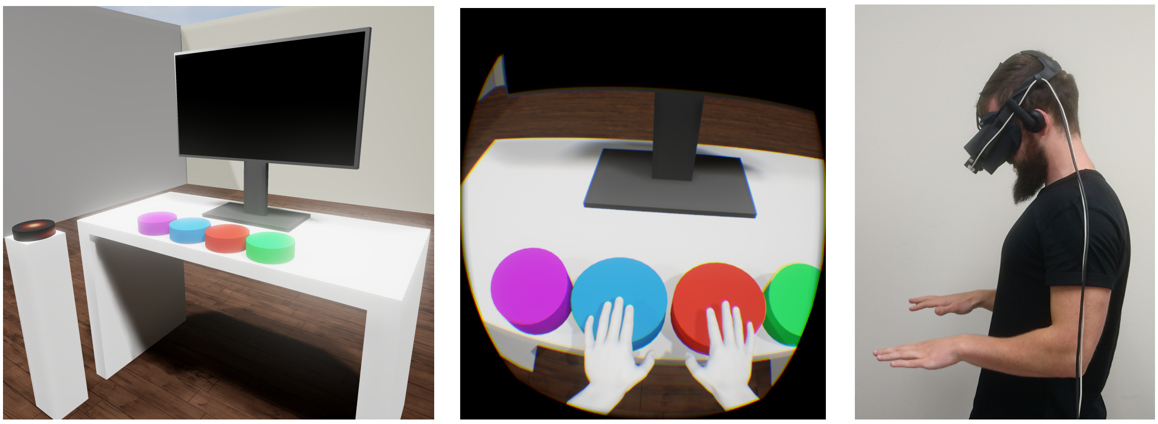
This is the case in [10], where they highlighted that users appeared to become tired when using the Leap Motion, having to hold their hands above the Leap Motion when mounted in a desktop configuration.

To improve driving pleasure in autonomous vehicles Manawadu et al. [11] used the Leap Motion to give the driver some lateral and longitudinal control of the vehicle. However, they observed that drivers found it difficult to input the gestures exactly inside the interaction space. The interaction space, which was desk mounted, was not in a comfortable position, from the upper chest to the users chin.

Vosinakis et al. [12] found that half of the participants reported arm fatigue during an engraving task when using the Leap Motion for Cycladic Sculptur. The Leap Motion was mounted in desktop mode with participants having to hold their hands above the device. The authors recommended that participants not hold their hands out at a stretched position for more than 20 seconds at a time. This recommendation is not practical for interacting in VR, interaction with VR should not be contained to 20 second bursts.

Lee et al. [13] evaluated adding a touch screen to the front of a GearVR headset [14] as a means of input to the mobile HMD. They attached the touch screen to the front of the HMD pointing outward, a participant raised their hands in front of their face and touched the screen to interact. They noted that 15 out of 20 participants experienced neck and arm fatigue when interacting with the touch screen on front of their face.

Al-Megren et al. [15] conducted a shoulder fatigue study, using both subjective and objective measures. The objective measures involved using surface Electromygraphy (SEMG) to monitor three muscles on each arm. They tested horizontal and vertical multi touch displays for arm fatigue when interacting, subjective measures showed arm fatigue for both horizontal and vertical interactions. However, objective measures showed a significant level of muscle fatigue on the middle deltoids and the non-dominant extensor digitorum for the vertical configuration only. This shows that participants shoulders were suffering from fatigue when interacting on a vertical panel, or up in front of their face. The authors noted that their results have clear implications on interaction design for large interactive displays, noting that vertical displays, while acceptable for short periods of time, are not suitable for frequent use. Whilst this study was conducted using interactive touch screens, the same applies to interacting with tracked hands in VR, specifically with



(a) Scene view of desk and monitor with down pressing buttons (b) User view of Down condition (c) Interaction posture of Down condition with original mount

Figure 2: Down Condition

the Leap Motion. This is because to achieve the best tracking a participant must interact with a vertical plane parallel to the device, provided that participant is looking forward.

To help reduce shoulder fatigue, Vuibert et al. [16] designed the width of the tracking volume to reside between the hip and the shoulder of the participants. In other work, researchers at NASA incorporated pointing rather than hand positioning to move the cursor in a VR menu. This allowed the user greater flexibility in the positioning of the arms and hands. It also reduced fatigue and improved accuracy [17].

In sum, there are motivations for making the interaction with VR and the use of the Leap Motion more ergonomic or user friendly. The literature shows that participants interacting with their arms raised will get fatigued, this also happens to be where the Leap's tracking is most accurate.

3 DEVICE AND MOUNT SETUP

In order to shift the optimal tracking volume of the Leap Motion to a position that is more comfortable for the user, the device was angled downward. In order to do this a custom angled mounting bracket was created. Using a DaVinci 1.0 [18] 3D printer various degrees of angled mounting brackets were printed. These brackets attached into the clip that holds the original, official Leap Motion mount. Initially 30, 45, 60 and 90 degree angled mounts were created. Though through preliminary testing, all but the 30 degree mount were deemed too large. The standard Leap Motion mount can be seen in Figures 1c and 2c, the 30 degree angled mount can be seen in Figure 3c. The mounts were attached onto an Oculus Rift CV1.

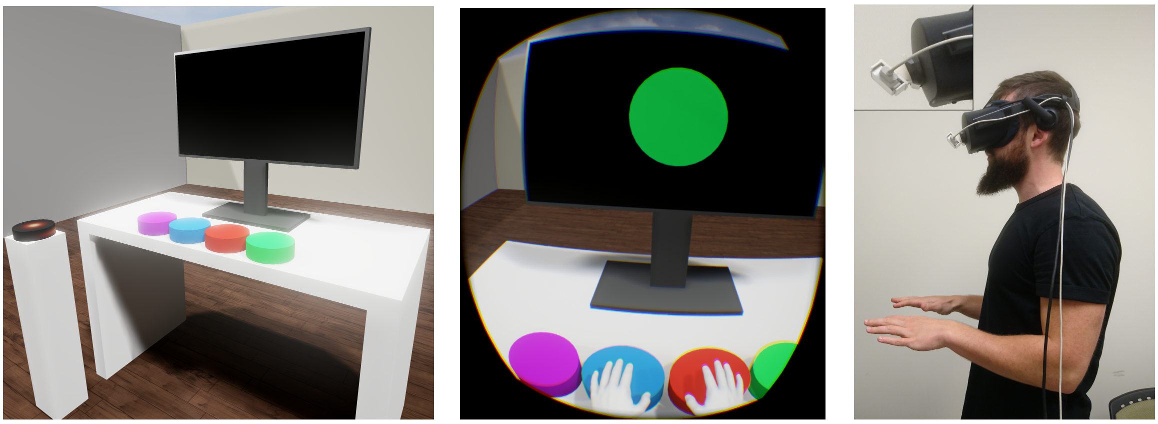
4 USER STUDY

A total of 15 people took part in the user study with an average age of 27. 60% were male and the remaining 40% female. 74% of participants were right handed with the remaining 26% left handed

Interaction with VR is task dependant [19], so the task in the present study was designed to mirror a generic task where the user is providing inputs dictated by the information being presented on a display. Because of the nature of the original Leap mount this type of task becomes difficult as in order to insure minimal tracking losses the user interaction has to be moved up, in front of the user. The input task required participants to press virtual buttons whose colours corresponded with the colour presented on a virtual display as quickly and accurately as possible. The scene was developed using Unreal Engine 4.13. Within the scene there was a rendered computer monitor, (Figures 1a,2a,3a), circles of a specific colour would appear on the monitor, and the user would have to hit the corresponding button. There were four colours available, these were randomly generated to appear on the monitor. Each colour was displayed on the monitor for 500ms. Participants had one second to respond in total. The locations of the four coloured buttons were randomised for each condition. All trials were conducted while participants were standing.

The user study consisted of three conditions counterbalanced across participants, with 100 trials per condition, these were spilt into blocks of 20. The participants started each block of 20 by pressing a start button to their left (Shown in Figure's 1a,2a,3a).

Condition one consisted of buttons that faced the participant (Forward pressing buttons), raised on a stand, this can be seen in Figure 1. These buttons were parallel to the screen and to the Leap Motion. For condition one the Leap Motion was mounted in its original official mount. A view from the participants perspective can be seen in Figure 1b. It should be noted here that both the displayed colour and the interaction buttons are within the participants FOV. We will refer to condi-



(a) Scene view of desk and monitor with down pressing buttons (b) User view of Angled condition (c) Interaction view of the Angled condition, with the angled mount

Figure 3: Angled Condition

tion one as the Forward (Buttons) condition. Condition two consisted of buttons on the desk that the rendered computer monitor was placed on, shown in Figure 2a. This is more a comfortable position for the participant to hit the buttons, again for this trial the Leap motion was mounted in its original position. However, from the participants perspective (Figure 2b), only one of either the displayed colour or the buttons can be seen at a time, the FOV is not large enough to capture both. We will refer to condition two as the Down (Buttons) condition. Lastly, the third condition (Figure 3a) used the 30 degree angled mount, like the second trial the buttons where placed on the desk for a more comfortable experience. In contrast to the Down condition, our modified setup with the angled mount allows for both the buttons and the displayed screen colour to be seen at the same time, within the participants FOV (Figure 3b), whilst also providing a more comfortable interaction environment. Condition three will be referred to as the Angled (Mount) condition.

Participants completed a short survey after the completion of each experimental condition to subjectively assess each condition. Participants rated their level of agreement from 1 (disagree) to 7 (agree) on the following statements:

1. I could easily press the correct buttons with the virtual fingers.
2. I often hit buttons I did not mean to hit.
3. It was easy to move the virtual hands where I wanted.
4. It was frustrating trying to hit the correct buttons in the virtual environment.
5. The virtual hands often disappeared when I was trying to press the buttons.

The expected results are shown in Table 1. Accuracy is defined as the correct number of displayed colours matched with a hit on the correctly coloured button, before a new colour has appeared on the monitor, only the first hit counts. Tracking losses were measured as the number of times one or more hands was not visible in VR, this is because both hands were required for the task. User comfort was quantified subjectively, asking the participants if they felt fatigued after each condition. The direction view vector of the HMD was recorded to allow for tracking of gaze direction and height. Response times were also recorded for each condition.

5 RESULTS

Dependant measures were each analysed in separate one-factor repeated measures ANOVAs with three levels (Condition: Forward, Down, Angled). Comparisons across the levels were made using 95% CI's (Confidence Intervals) generated from the ANOVAs [20].

Tracking Loss. Of primary interest was that the angled mount substantially reduced tracking losses relative to the other conditions, $F(2,28) = 13.874, p < .001, part-eta = .4498$. As shown in Figure 4, there were significantly fewer tracking losses in the Angled condition than in the Forward and Down conditions. In fact, the number of tracking losses in the Angled condition was negligible with a mean of 0.66 times, indicating that the Leap Motion system with the angled mount was able to maintain near 100% tracking of the users hands.

Accuracy. The Analysis of the mean accuracy scores showed a significant effect of condition, $F(2,28) = 11.228, p < .001, part-eta = .445$ As shown in Figure 5 participants were significantly less accurate at hitting the correct virtual button in the Down condition than the Forward and Angled conditions. The finding that the accuracy did not differ between the Forward and the Angled conditions is important as it shows that the most effective tracking volume has been moved.

Table 1: Expected Results

Forward Condition	Down Condition	Angled Condition
High accuracy	Low accuracy	High accuracy
Low tracking loss	High tracking loss	Low tracking loss
User discomfort (Arms)	User discomfort (Neck)	User comfort
Low gaze variation	High gaze variation	Low gaze variation

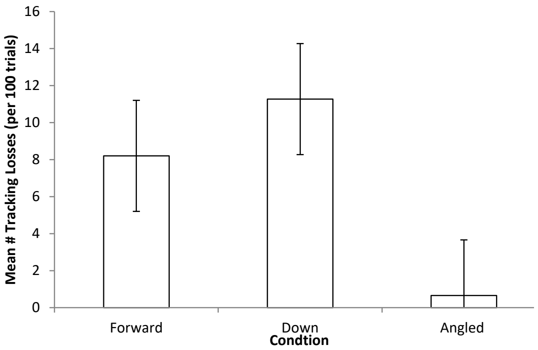


Figure 4: Tracking Losses

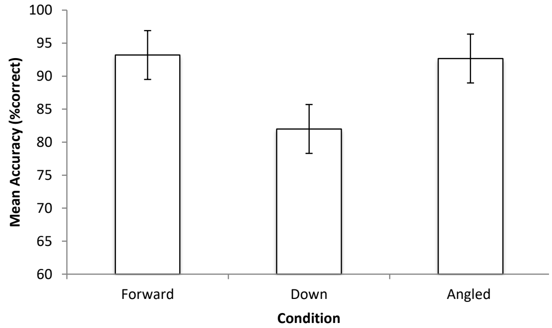


Figure 5: Accuracy

Response Times. Response times were measured from the initial presentation of a target to the point at which a virtual button was hit. Overall, 7.4% of the response time data was lost due to mechanisms used to make the buttons 'bounce'. The buttons work by linear interpolating between two positions. If the participant did not move their hand away quick enough and were late in reacting to the displayed colour, the system registered a hit for the next displayed colour, at an instant response time of zero seconds. It is interesting to note that the more data was lost in the Down (12.3%) condition as compared to 5.3% of the Forward condition and the Angled condition at 4.4%.

An analysis of the mean correct response times showed a significant effect of condition, $F(2,28) = 5.827, p = .008, part - eta = .294$. Response times were faster in the Forward (714 ms) condition than in the Down (733 ms) and the Angled (755 ms) conditions. This was expected as in the Forward condition the response buttons and the target were both presented in the same forward field of view. Response times did not differ significantly between the Angled and the Down conditions.

Gaze Variation. Gaze Variation was calculated as the standard deviation of gaze location across each of the 100 trials for each condition. The gaze variation is measured as z height variation from the HMD view vector. There was a significant effect of condition on gaze variation, $F(2,28) = 23.383, p < .001, part - eta = .625$. As shown in Figure 6, gaze variation was larger in the Down than the Forward and Angled conditions. This reflects the fact that in the Down condition participants had to move their gaze from the targets in the up position in order to see the virtual buttons in the down location. Gaze variation did not differ significantly between

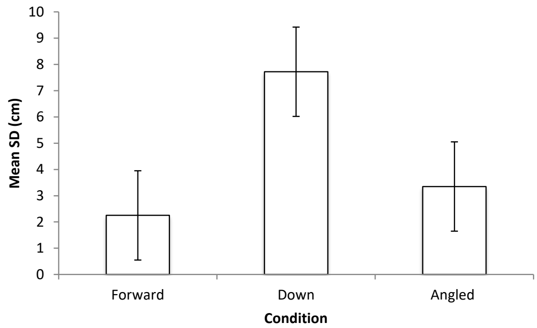


Figure 6: Gaze Variation

the Forward and the Angled conditions. Gaze variation was understandably low in the Forward condition as both the targets and the virtual buttons were positioned in the same forward field of view. The low gaze variation in the Angled condition suggests that with the 30 degree mount participants were able see their hands while also seeing the target stimuli.

Survey Responses. Analysis of the survey results indicated that two of the questions indexed a significant impact of condition. The first question asked the participants how easily they could press the buttons with the virtual tracked fingers. Participants indicated that the Forward condition had the highest score (Higher is better) out of 7 at 5.29, with the Angled condition following closely at 4.96, the Down condition trailed both these with an average answer of 3.79. The second question asked how often the participants felt the hands disappeared when they were trying to press a button, again out of 7. The Angled condition achieved the lowest score (Lower is better) at 2.29, with the Forward condition receiving 3.04 and the Down condition the highest at 3.96.

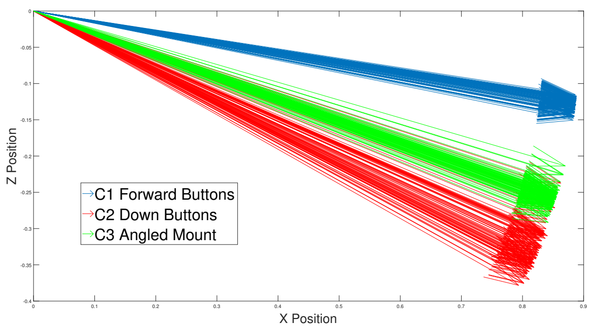


Figure 7: View Vectors

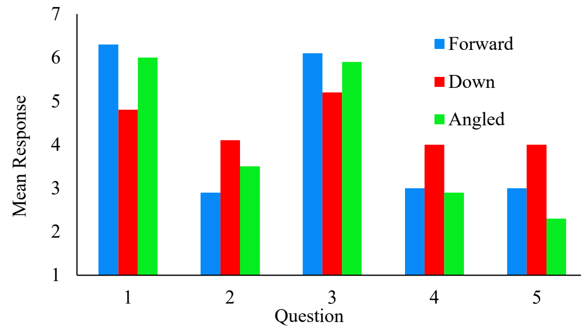


Figure 8: Survey questions results.

6 DISCUSSION

Due to the high variability in gaze location in the Down condition, there was a dramatic difference in the numbers of times that tracking was lost (Figure 4) over the 100 trials in each condition. For the angled condition, there was an average of 0.66 tracking losses over 100 trials. In contrast, there was an average of 11.27 tracking losses per 100 trials on the Down condition. Because the Leap is mounted on the head, every head movement changes the location of the Leap tracking volume thus increasing the likelihood of a tracking loss occurring.

As predicted the Down condition had the lowest accuracy while there was no difference between Forward and Angled conditions. The lack of difference in the accuracy between the Forward and Angled conditions is because the angled mount allows for the emulation of similar characteristics of the Forward condition, in a more comfortable manor. In the Forward condition the forward buttons, target stimuli and hands are all located in the users FOV. Using the angled mount allows for the buttons, target stimuli and hands to all be within the users field of view when interacting with down buttons, which they are not in the Down condition. The accuracy on the Down condition was well above chance so although more challenging, the task was of reasonable difficulty.

Gaze location can be used as a metric for task comfort. Moving the head up and down or standing with the neck angled down for long periods can lead to a host of health problems [21]. For this metric, we are concerned with the height component of the view vector. In this case the z component represents gaze height. Ergonomists recommend that one's gaze be aligned parallel to the floor. This insures the neck in aligned vertically with the spine. In relation to this, a higher z value, or as the value approaches zero (See Figure 7) the more optimal the value is. In Figure 7 the view vectors from an arbitrary point (HMD Origin) are displayed. All 100 trials per condition are averaged across participants. Blue arrows represent the Forward condition. As predicted, the Forward condition has the highest gaze height with little variability which means participants did not move their head much. Ergonomically, the Forward condition is the best position for the neck. However, the Forward condition requires participants to hold their arms in front of their face for the majority of the trials.

The Down Condition (Red) had the lowest gaze height and highest gaze variability making it the least ergonomic. The use of the angled mount resulted in an improvement in the gaze height and a reduction of gaze variability. It was initially assumed that use of an angled mount of 30 degrees would allow for an improvement of 15 degrees between the Down and Angled conditions. However, when all the trials are averaged out, and the angle between the upper x axis (parallel to the floor) and these gaze vectors are calculated, this assumption was shown to be incorrect. The angle between the x axis and the Forward conditions gaze vector is -8.29 degrees. The angle for the Down condition is notably larger, at -21.71 degrees. The angled mount improves this for the Angled condition to -16.89 degrees, an improvement of 4.82 degrees (4.87cm z height difference).

Response times were significantly faster in the Forward condition when the buttons were elevated up in front of the participants and close to where the targets were displayed. We hypothesized that the fastest response times would occur in the Angled condition because participants hands were in the most comfortable position while still being tracked. However, it is likely that due to the proximity of the buttons and the target stimulus, although less comfortable, the Forward condition allowed for quicker responses. We hypothesized that the Down condition would result in the slowest response times because participants had to move their heads from trial to trial in order to keep the Leap hands in view. The results reveal this not to be the case. It is possible that there was a speed accuracy trade-off in the Down condition with participants being relatively quick but making more errors and resulting in more tracking losses.

Although subjective, a number of participants (three), mentioned explicitly that their shoulders were feeling fatigued, also worth noting is that these participants ran the study in one of the counter balanced orders resulting in them completing the forward condition last, the most taxing.

In the Forward condition, the optimal position for tracking (Figure 1c) consisted of the user looking straight ahead and bringing their hands into view. However, after a number of trials participants began to lower their arms and look down slightly. They lowered their arms into what we call the "T-Rex" position, that is their elbows tucked tight into their sides for support with their hands up and pulled back parallel to their shoulders. From this position participants in the Forward condition raised their hands up into the field of view to push a virtual button. Had a default resting position been set, or a line drawn in front of them in VR, where the participant had to keep their hands above for the duration of the condition, there may have been a similar amount of tracking losses to the Angled condition.

The participants were asked to answer five questions after each condition. Answers ranged from 1-7, 1 meaning disagree, 4 neither agree nor disagree and 7 agree. Comparing the participants survey answers for both down button conditions (Down and Angled) it becomes apparent that they agreed the angled mount made it easier to press the correct buttons. This is also clear for the second significant question relating to tracking issues, there is a huge difference in the amount of times tracking is lost across all conditions, the participants also acknowledged this. The participants answers for the Down and Angled condition are almost exactly opposite ends of the agree and disagree scale, with scores of 4.96 and 3.29 (1 to 7 range, 4 neither agree nor disagree), they both edge into strongly disagree and strongly agree for how well they thought the hands were tracked, this is shown in Figure 8. The participants answers reflect the results measured objectively, they recognised the benefits of the angled mount.

During the Forward condition the hit location on the button was recorded, this was recorded as we hypothesized that the vertical location (z) of the hit would drop if they fatigued, resulting in an objective measure for fatigue. There was no significant relationship between the location of button press and the trial number, meaning the data does not support the hyposthsis that peoples hits lowered as the trials went on. This is not to say they were not fatigued but this measure does not capture it. We know that participants will get fatigued based on previous SEMG monitoring studies [15], and while anecdotal we believe the "T-rex" position they default to during the Forward condition reflects this.

7 CONCLUSIONS AND FUTURE WORK

This paper introduced and evaluated a custom 3D printed angled mount for use with the Leap Motion and HMD's. Changing the orientation of the optimal tracking volume for a Leap Motion attached to a HMD improves user comfort and allows a more natural posture to be adopted when using such devices for a prolonged period of time. The mount allows for a person to have their arms at a comfortable 90 degrees to their body, rather than holding them raised in front of their face, which can result in fatigue. 15 participants completed a task to evaluate the effectiveness of the new angled mount. Our hypotheses of the improvements the angled mount would bring were correct. Not only did the angled mount achieve the accuracy of the optimal tracking Forward condition (Figure 5), it eliminates tracking losses, in comparison to both the Forward and Down conditions (Figure 4).

Alongside the expected behavioural improvement, the analysis provides evidence that the biomechanical mechanism by which the test manipulation is expected to improve performance is detectable itself in gaze measurements, with the angled mount cutting gaze variation by over 50%. This reduction in gaze variation can improve neck comfort. Using the angled mount allows for optimal tracking, comfortable interaction and reduced head movement.

The angle of the mount studied may have actually been too large. We believe the optimal angle to be somewhere between 15 and 30 degrees, so as to reduce the impact of any possible interactions above the headset. As interaction with VR is task dependant [19] we foresee a use for an adjustable mount in the future. This mount could feed its angle into Unreal Engine, allowing for on the fly customisation based on the task at hand.

Virtual reality is centred around experiencing new sights and environments, this is impacted negatively when having to look down at what is being interacted with, rather than being engaged with a greater portion of what is displayed in the environment. In everyday life interaction is mostly completed in the peripherals of our vision. The use of the angled mount affords more natural interactions utilising more of the peripheral vision, like that of everyday interactions.

ACKNOWLEDGEMENTS

To the ACE lab, many thanks for an awesome Canadian adventure, without whom this would not be possible.

REFERENCES

[1] OCULUS Inc, 2015. URL `https://www.oculus.com/en-us/`.

[2] HTC Corporation, 2016. URL `https://www.htcvive.com/uk/`.

[3] Leap Motion Inc. Leap Motion Inc, 2015. URL `https://www.leapmotion.com/`.

[4] Bengt Ahlström, Sören Lenman, and Thomas Marmolin. Overcoming touchscreen user fatigue by workplace design. In *Posters and Short Talks of the 1992 SIGCHI Conference on Human Factors in Computing Systems*, CHI 92, pages 101–102, New York, NY, USA, 1992. ACM.

[5] Andrew Sears. Improving touchscreen keyboards: design issues and a comparison with other devices. *Interacting with computers*, 3(3):253–269, 1991.

[6] J. K. Sharma, R. Gupta, and V. K. Pathak. Numeral gesture recognition using leap motion sensor. In *2015 International Conference on Computational Intelligence and Communication Networks (CICN)*, pages 411–414, Dec 2015.

[7] M. Sreejith, S. Rakesh, S. Gupta, S. Biswas, and P. P. Das. Real-time hands-free immersive image navigation system using microsoft kinect 2.0 and leap motion controller. In *2015 Fifth National Conference on Computer Vision, Pattern Recognition, Image Processing and Graphics (NCVPRIPG)*, pages 1–4, Dec 2015.

[8] Jože Guna, Grega Jakus, Matevž Pogačnik, Sašo Tomažič, and Jaka Sodnik. An analysis of the precision and reliability of the leap motion sensor and its suitability for static and dynamic tracking. *Sensors*, 14(2):3702–3720, 2014.

[9] Frank Weichert, Daniel Bachmann, Bartholomäus Rudak, and Denis Fisseler. Analysis of the accuracy and robustness of the leap motion controller. *Sensors*, 13(5):6380–6393, 2013.

[10] D. E. Holmes, D. K. Charles, P. J. Morrow, S. McClean, and S. M. McDonough. Using fitt's law to model arm motion tracked in 3d by a leap motion controller for virtual reality upper arm stroke rehabilitation. In *2016 IEEE 29th International Symposium on Computer-Based Medical Systems (CBMS)*, pages 335–336, June 2016.

[11] U. E. Manawadu, M. Kamezaki, M. Ishikawa, T. Kawano, and S. Sugano. A haptic feedback driver-vehicle interface for controlling lateral and longitudinal motions of autonomous vehicles. In *2016 IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*, pages 119–124, July 2016.

[12] S. Vosinakis, P. Koutsabasis, D. Makris, and E. Sagia. A kinesthetic approach to digital heritage using leap motion: The cycladic sculpture application. In *2016 8th International Conference on Games and Virtual Worlds for Serious Applications (VS-GAMES)*, pages 1–8, Sept 2016.

[13] Jihyun Lee, Byungmoon Kim, Bongwon Suh, and Eunyee Koh. Exploring the front touch interface for virtual reality headsets. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, pages 2585–2591. ACM, 2016.

[14] Samsung. GearVR, 2016. URL `http://www.samsung.com/global/galaxy/gear-vr/`.

[15] Shiroq Al-Megren, Ahmed Kharrufa, Jonathan Hook, Amey Holden, Selina Sutton, and Patrick Olivier. *Comparing Fatigue When Using Large Horizontal and Vertical Multi-touch Interaction Displays*, pages 156–164. Springer International Publishing, Cham, 2015. ISBN 978-3-319-22723-8.

[16] Vanessa Vuibert, Wolfgang Stuerzlinger, and Jeremy R Cooperstock. Evaluation of docking task performance using mid-air interaction techniques. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction*, pages 44–52. ACM, 2015.

[17] Stephen R Ellis. Using virtual menus in a virtual environment richard h. jacoby sterling software nasa ames research center, m/s 262-6 moffett field, ca. 94035. *Visual Data Interpretation: 10-11 February 1992, San Jose, California*, 1668: 39, 1992.

[18] AYZ Printing. da vinci 1.0, 2016. URL `http://us.xyzprinting.com/us_en/Product/da-Vinci-1.0`.

[19] Kay M. Stanney, Ronald R. Mourant, and Robert S. Kennedy. Human factors issues in virtual environments: A review of the literature. *Presence: Teleoper. Virtual Environ.*, 7(4):327–351, August 1998. ISSN 1054-7460.

[20] Jerzy Jarmasz and Justin G Hollands. Confidence intervals in repeated-measures designs: The number of observations principle. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, 63(2):124, 2009.

[21] Dennis R Ankrum and Kristie J Nemeth. Head and neck posture at computer workstations-what's neutral? In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 44, pages 5–565. SAGE Publications, 2000.