

# Influence of Comfort on 3D Selection Task Performance in Immersive Desktop Setups

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## Abstract

Immersive virtual environments (IVEs) have the potential to afford natural interaction in the three-dimensional (3D) space around a user. However, interaction performance in 3D mid-air is often reduced and depends on a variety of ergonomics factors, the user's endurance, muscular strength, as well as fitness. In particular, in contrast to traditional desktop-based setups, users often cannot rest their arms in a comfortable pose during the interaction.

In this article we analyze the impact of comfort on 3D selection tasks in an *immersive desktop setup*. First, in a pre-study we identified how comfortable or uncomfortable specific interaction positions and poses are for users who are standing upright. Then, we investigated differences in 3D selection task performance when users interact with their hands in a comfortable or uncomfortable body pose, while sitting on a chair in front of a table while the VE was displayed on a head-mounted display (HMD). We conducted a Fitts' Law experiment to evaluate selection performance in different poses. The results suggest that users achieve a significantly higher performance in a comfortable pose when they rest their elbow on the table.

**Keywords:** 3D interaction, 3D selection, head-mounted displays

## 1 Introduction

Since the advent of 3D cinema and with 3D television and 3D gaming coming up in the consumer market, stereoscopic visualization is getting more and more important for a range of application fields. Moreover, advances in the field of unobtrusive body tracking, such as the Microsoft Kinect or the Leap Motion controller, afford natural interaction with 3D data sets. While stereoscopic display supports near-natural spatial impressions of virtual objects and scenes, using the hands and body to touch and manipulate virtual objects provides an intuitive direct interface for interaction with stereoscopically displayed 3D content [SBK<sup>+</sup>12]. Immersive virtual environments (IVEs), such as tracked head-mounted displays (HMDs) or CAVEs, thus have the potential to provide natural and intuitive interaction with virtual objects located in the proximity of the user's viewpoint. If an interactive virtual object is located within arm's reach, users can perform natural reach and touch gestures similar to the real world, whereas different IVEs provide users with different affordances for traveling to objects that are located at a larger distance.

However, since such interactive virtual objects could be located anywhere within arm's reach, the question arises how its position in different regions around the user's body affects comfort as well as interaction performance. Interaction in regions that users judge as comfortable, i. e., feeling physically relaxed without any pain or displeasing posture, could be beneficial for long interaction sessions. Performance may also differ depending on the muscle strength or flexi-

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bility of the user, and may be affected by the use of different muscle groups and levels of energy expenditure of the body. Well before Hollywood popularized 3D direct interaction in mid-air, e.g. in different movies and TV series, such as *Minority Report* or in the *Iron Man* trilogy, VR researchers and practitioners had observed through recorded participant comments and occasional complaints, that such mid-air interactions can lead to arm fatigue and discomfort [BKLP04]. They costs significantly more muscular energy than desktop interaction, and may thus not provide high performance during prolonged use, although the performance during the first minutes may be encouraging. In our previous work [HBF<sup>+</sup>13] we compared direct mid-air selection performance between users interacting in comfortable or uncomfortable regions within arm's reach in a HMD setup. Our results suggested that subjects made fewer errors but required more time when interacting in a comfortable region. We found no significant main effect of the uncomfortable and comfortable condition, which motivated us to consider situations in which a more significant distinction can be made between comfortable and uncomfortable poses. Further details about this pre-study can be found in Section 3.

In this article we compare direct 3D selection performance between users interacting in comfortable or uncomfortable poses in an *immersive desktop setup*. In such immersive desktop setups, users sit on a chair in front of a table while the VE is displayed on a head-mounted display (HMD) (see Figure 4). First, we performed a pre-study in which we determined regions that subjects rated as comfortable or uncomfortable. Then, we conducted a Fitts' Law experiment in which we compared 3D selection performance between users interacting in a comfortable and uncomfortable pose in the immersive desktop setup. In the comfortable pose, users rested the elbow of their dominant arm on the table, whereas in the uncomfortable pose, the users had to interact in mid-air above the table surface without resting the elbow.

In summary, our contributions include the

- analysis of comfortable and uncomfortable regions within arm's reach,
- comparison of selection performance in comfortable and uncomfortable poses in an immersive desktop setup, and
- guidelines for designing 3D user interfaces for immersive desktop setups.

This article is structured as follows. Section 2 gives an overview of related work. Section 3 summarizes the pre-study in which we identified comfortable and uncomfortable regions for 3D interaction in an upright position. Section 4 describes the conducted Fitts' Law experiment in the immersive desktop setup. Results are presented and discussed in Section 5. Section 6 concludes the article.

## 2 Related Work

**3D Selection** 3D interaction and 3D selection, in particular, have been in the focus of many research groups over the last decades. Although direct interaction, meaning coupled or superimposed hand positions to allow selection and interaction, provides the most natural type of interaction with virtual objects, it is often not possible to use direct selection for objects that are not located within arm's reach.

This led to the development of a multitude of indirect interaction techniques, offering the possibility to select distant objects but decoupling the virtual hand position from the user's actual hand position. Different indirect interaction techniques have been proposed, such as the Go-Go technique [PBWI96] and HOMER [BH97], which can provide users with the ability to interact with virtual objects in vista space, the region within eyesight but beyond action space [SB85], by nonlinear scaling of hand positions within arm's reach. In particular, these techniques make use of the entire reachable space of a user's arms during interaction with distant objects, which may prove tiresome when constantly interacting at a distance, and may thus result in degraded performance over time. On the other hand, Mine et al. [MBS97] observed that such indirect interaction techniques result in degraded performance during interaction with virtual objects located within arm's reach. According to their results, direct interaction leads to significantly higher performance than manipulation of objects at a distance from the user's hand. Most results from similar studies agree on the point that optimal performance may be achieved when visual and motor spaces are superimposed or coupled closely [Dja98, LL07, WM99]. In recent years, the utility of bimanual interaction for different fields has been investigated, e.g. for volumetric data [LB13, UWG<sup>+</sup>09].

However, it is still an open research question, how the position of virtual target objects located within arm's reach may affect interaction performance. Di-

rect interaction is subject to perceptual limitations, e. g., the vergence-accommodation mismatch, ghosting or double vision, which can result in significant misperception effects [BSS13b, BSS13a, CKC<sup>+</sup>10]. Depending on the location of virtual objects, users may be unable to discriminate interrelations or perceive distances to objects to be smaller or larger than they are displayed [LK03]. Distortions like that do not appear in full-cue real-world environments and may be related to limitations of current technology to correctly reproduce naturally occurring cues from the real world perfectly [WCCRT09]. Moreover, internal representations of space are influenced and updated by both visual and motoric input, which may affect interaction performance [WGTCR08, Tho11]. Due to varying energy expenditure between users based on differences in strength and endurance of arm muscles, interaction performance in mid-air within arm's reach in IVEs may be affected by different factors related to the ergonomics of direct interaction. In particular, contributing factors may include interaction duration, hand and arm postures, frequency of movements, and comfort. Bigger muscle groups, like arm muscles, are usually necessary for direct mid-air interaction and Card et al. found that bigger muscle groups tend to be less precise than smaller muscle groups, such as fingers and wrists [CH93]. Previous studies have compared fatigue in semi-immersive, Fishtank-VR environments to classic mouse setups, manual and bimanual interaction, utilizing an arm rest [Sha98]. They showed that bimanual, 6DOF interaction does not induce significantly more fatigue than mouse and keyboard input.

**Fitts' Law** Fitts' Law describes the tradeoff between speed and accuracy in selection tasks [Fit54]. Selections by touching or grasping objects with a user's hands can be split up into two phases, the ballistic phase and the correction phase [LPSH01]. The ballistic phase consists of focusing on the target object and bringing the hand in the proximity of the goal by using proprioceptive motor control. After that, visual feedback is used in the correction phase in order to incrementally reduce the distance from the hand to the goal. Fitts' Law predicts the movement time  $MT$  for a given target distance  $D$  and size  $W$ . They are brought together in a log term which describes the difficulty of the task overall with  $MT = a + b \cdot \log_2(\frac{D}{W} + 1)$ . The values  $a$  and  $b$  are empirically derived for given setups. The *index of difficulty* (ID) is given by the log term and indicates overall task difficulty; smaller and/or far-

ther targets result in increased difficulty. The formula has been extended in order to get effective measures. The error rate is adjusted to 4% by resizing targets to their effective width  $W_e$ . This is supported by an international standard [Int00]. By calculating the average of the measured movement distances,  $D_e$  can be determined. With that, the effective throughput can be computed as a useful combination of speed and accuracy:  $TP = \log_2(\frac{D_e}{W_e} + 1) / MT$ . The validity of Fitts' Law for 3D interaction has been researched in the last years. Results from studies of several research groups imply that Fitts' Law is indeed valid for the kinematics of arm movements in a 3D interaction space [DKK07, MMD<sup>+</sup>87, MI08]. In addition, Wingrave and Bowman [WB05] showed that Fitts' Law still holds when pointing in VEs. They observed that  $D$  was related to the amplitude of the movement, and  $W$  to the visual size of the target. Poupyrev et al. [PWBI97] defined the size of an object  $W$  according to the vertical and horizontal angles, that the object occupies in the user's field of view (FOV).

Similarly, Kopper et al. [KBSM10] propose a modification of Fitts' Law as a model for human performance in distal pointing tasks. Their model is based on angular amplitude and angular width as they argue that, contrary to classic 2D Fitts' Law tasks, the objects are floating in 3D space and the sizes and distances depend on the user's position, which can be solved by using angular measurements.

Ha and Woo adopt Fitts' Law for 3D tangible augmented reality environments with virtual hand metaphors [HW10] by using the model established by Grossman et al. [GB04], which was based on a 3D objects arranged on a 2D plane.

Murata and Iwase [MI01] proposed an extension of Fitts' Law for 3D pointing tasks introducing a directional parameter into the model. Further studies investigating whether object selection in 3D mid-air can be modeled by Fitts' Law are described by Ware and Balakrishnan [WB94]. Finally, Teather and Stuerzlinger [TS11] found that using the simple Euclidean distance is viable enough for systems using a fish-tank virtual reality (VR) system like in our setup.

### 3 Pre-Study

In this section we briefly summarize the pre-study that we conducted to determine comfortable regions in 3D mid-air interaction within arm's reach, as well as the first study we conducted to find an influence of com-



Figure 1: Position grid as used in the pre-study.

fort on selection performance. Further details about this study can be found in [HBF<sup>+</sup>13].

### 3.1 Study Design

In a pre-study we recruited 27 participants (16 female, 11 male, age 14 - 57,  $M = 31.5$ ) and asked them to take 26 predefined positions with their dominant hand and arm (see Figure 1). All subjects were right-handed. As illustrated in Figure 1, we defined the positions based on a grid with two different depths and six different heights. The different depths were realized by instructing the subjects to flex or to stretch out their arms.

In order to prevent a bias on the results, subjects received minimal instructions about the goals of the study. We randomized the positions and every subject had to hold every position for exactly 10 seconds indicated by an acoustic signal. After every position the subjects had to judge the comfort of that position using a 5-point ranking scale (0: very comfortable – 4: very uncomfortable). The total time per subject was less than 20 minutes.

### 3.2 Results

We compared the means of the comfort values of every position (see Figure 2). The results imply that the most comfortable way to interact is close to the body with elbow flexion. The most comfortable positions had a mean below 1: positions 5, 6, 7, 10, and 11. In contrast, the least comfortable positions are the positions 3, 13, 24, 25, and 26. As illustrated in Figure 3, we found that positions with flexed arms are mostly considered more comfortable than positions with stretched-out arms.

In the first study, described in [HBF<sup>+</sup>13], we compared direct mid-air selection performance between users interacting in comfortable or uncomfortable regions within arm's reach in a HMD setup while standing upright. The results of the pre-study were generalized into flexed arms at a distance of less than about 65% of the maximum arm's reach for comfortable positions and stretched-out arms at a distance of more than 65% of the maximum arm's reach for uncomfortable positions. For the study a Sony HMZ-T1 HMD was tracked in 6DOF by a 8 camera IOTracker while the subjects' index finger was tracked with a 3-DOF target. While we found a significant influence of the comfortable condition on the error distance, with larger errors in the uncomfortable condition, we did not find main effects of the comfortable condition on the error rate, movement time or throughput. However, we found a trend on the error rate with the mean error rate being lower for the comfortable condition. We also analyzed SSQ and SUS questionnaires but did not observe significant differences between the two conditions. However, all positions required some effort for the subjects. Also, the subjective opinion of our subjects clearly showed differences in the different conditions.

This motivated us to consider situations in which a more significant distinction can be made between a comfortable and uncomfortable pose (cf. Section 4).

## 4 Experiment

In this section we describe the Fitts' Law experiment in which we analyzed direct 3D selection in the user's arm reach in an immersive desktop-based HMD environment.

**Motivation** While we could find a significant main effect of comfort on selection performance measured

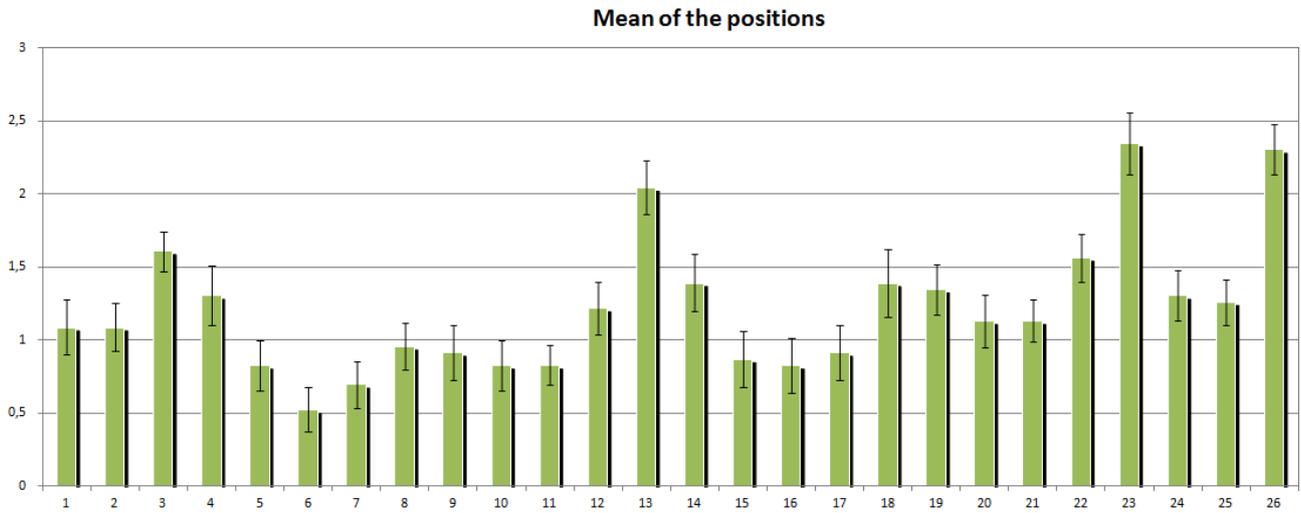


Figure 2: Means of the comfort values of every position.

by throughput in the previous studies, the subjective opinions, as well as the trends we found motivated us to investigate the influence of comfort in a further study.

Instead of defining stretched out arms as uncomfortable and arms with a degree of elbow flexion as comfortable, requiring participants to keep their arms aloft nonetheless, we decided to evaluate a different definition of comfort, namely an arm support. Needless to say, requiring participants to keep their arm aloft

is considered less comfortable than providing an arm rest for the participant to place their elbow on, removing the tension from the shoulder and arm muscles. Although the concept of comfort is broad and should not be overly simplified, we believe that a reduction of muscle tension over time is an adequate facet of the broad concept of comfort.

While the first evaluation was in an upright position, we decided to conduct the study in a seated position in both conditions, comfortable due to an arm support and uncomfortable without.



Figure 3: Heatmap illustration of comfortable and uncomfortable poses; red regions were evaluated as uncomfortable, green regions as comfortable poses.

#### 4.1 Participants

We recruited 12 subjects for our experiment. Nine of them were male, three were female (ages 19 - 36,  $M = 25.33$ ). All of the subjects were either students or professionals in human-computer interaction or media communication from the University of Würzburg. The students received class credit points for the participation in the experiment. Two subjects were left handed, the remaining 10 subjects were right handed. All subjects had normal or corrected vision.

Using the technique proposed by Willemsen et al. [WGTCR08] we measured the interpupillary distance (IPD) of each subject before the experiment started ( $M = 6.35$  cm,  $SD = .44$  cm). Additionally, we used the Porta and Dolman tests to determine the sighting dominant eye of subjects [MOB03]. The test revealed that two were left-eye dominant (2 male), whereas eight subjects were right-eye dominant (6 male, 2 female). For two subjects, both tests yielded

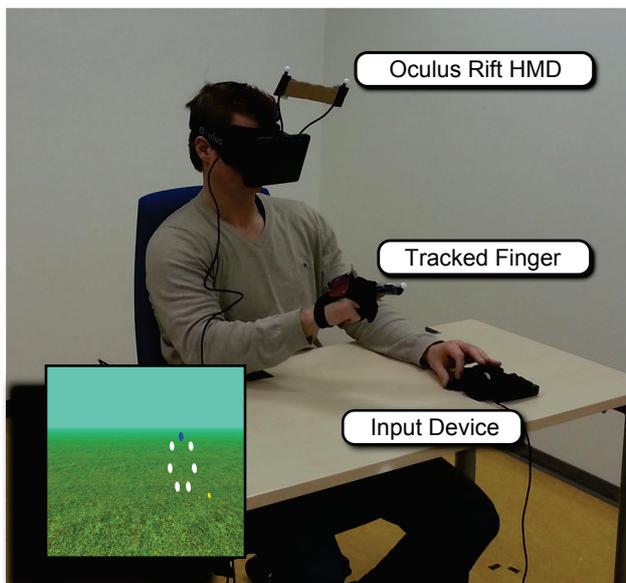


Figure 4: User during the experiment. The inset shows the user's view to the VE with the white and blue target spheres as well as the yellow sphere that visually represents the tracked finger tip.

different results (1 male, 1 female). We measured the lower arm length ( $M=37.00$  cm,  $SD=3.47$  cm) and calibrated the VE for each subject accordingly (cf. Section 4.2).

All subjects reported at least some experience with 3D stereoscopy (rating scale 0 = no, 4 = yes,  $M=3.42$ ,  $SD=.79$ ). Five subjects reported that they have participated in HMD studies before, and eleven subjects reported experience with HMDs (rating scale 0 = no experience, 4 = much experience,  $M=2.00$ ,  $SD=1.86$ ). The remaining seven subjects had no experience with HMDs. All subjects were naïve to the experimental conditions.

The mean of the total time per subject, including questionnaires and instructions was about 40 minutes. The mean time for performing the actual experiment while wearing the HMD was about 26 ( $M=25.52$ ,  $SD=06.24$ ) minutes. Subjects were allowed to take breaks in between trials.

## 4.2 Materials

As illustrated in Figure 4, subjects were instructed to sit in an upright position facing towards the cameras of the optical tracking system. A Razer Nostromo keypad was adjusted to a comfortable position for the non-dominant hand of the user. Subjects were instructed to keep their hand at that position during the experiment

to confirm their selections.

The experiment was conducted with the user wearing an Oculus Rift (Developer Edition) HMD with an attached active infrared (IR) target. The target was tracked by an optical WorldViz Precision Position Tracking (PPT X4) system with sub-millimeter precision for view-dependent rendering. We combined the PPT's optical heading with the inertial orientation of the Oculus Rift in order to provide robust head tracking without drifts. The Oculus Rift offers a horizontal FOV of approximately  $90^\circ$  and a vertical FOV of  $110^\circ$  at a resolution of  $1280 \times 800$  pixels ( $640 \times 800$  for each eye).

Additionally, we attached a single IR target to the index finger of the subject's dominant hand (see Figure 4). The virtual stimulus (see Figure 4(inset)) used in the experiment displayed a 3D scene, which was rendered with OpenGL on an Intel computer with a Core i7 3.8GHz CPU, 8GB of main memory and Nvidia GeForce GTX580 graphics card. For the Oculus Rift, we rendered the virtual scene side-by-side and applied a barrel distortion.

The targets in the experiment were represented by spheres. All target sphere for one trial were always visible and colored white, except for the current target. The current target sphere was colored blue when the marker was outside, and green when the marker was inside to give the subjects a visual cue. As common in Fitts' law tasks, the odd number of spheres were lighted in the order specified by the ISO 9241-9 standard [Int00]. As illustrated in Figure 5, each trial consisted of an arrangement of 7 target spheres, forming a circle with each sphere at the same distance to the subject's elbow.

## 4.3 Methods

We used a  $2 \times 2 \times 2 \times 3$  within-subject design with the method of constant stimuli for the experiment trials. In condition *comfortable* subjects rested their elbow on a table, whereas in condition *uncomfortable* subjects were not allowed to rest their arm during the trial.

In addition, we used two distances (8cm and 12.5cm) between spheres as well as two sphere radii (2cm and 3cm), resulting in four IDs (2.32bps, 1.87bps, 2.86bps, 2.37bps) representing a valuable range of task difficulties for such 3D user interface setups. IDs outside this range seemed impractical for 3D user interfaces, as the spheres would be either too

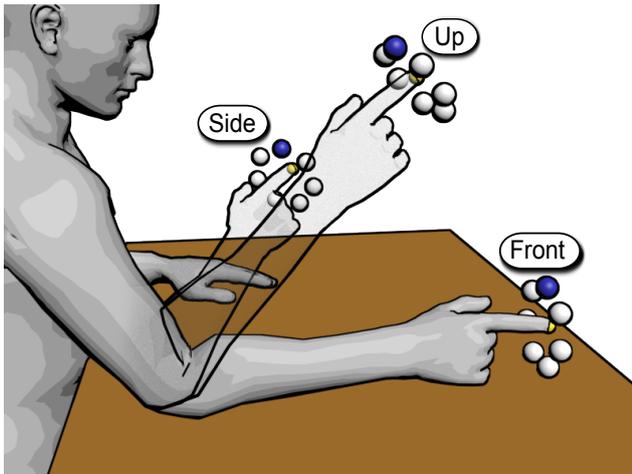


Figure 5: Schematic illustration depicting the three interaction positions. Only one ring of spheres was active during a single trial. The blue sphere depicts the target sphere. The yellow sphere depicts the sphere the user saw at the location of the fingertip.

large, taking up too much space or too small, to be precisely selected in mid-air.

The two sphere radii, two distances and three interaction positions were uniformly and randomly distributed. Each resulting condition was tested five times, resulting in 60 trials for the comfortable and uncomfortable condition respectively. We counterbalanced the order between subjects; half of the subjects started with the comfortable condition followed by the uncomfortable one and vice versa.

Following both oral and written instructions, for both conditions, subjects completed between 2 and 10 supervised training trials for the experimental phase to ensure that they understood the task correctly. Those training trials were excluded from the analysis.

Each trial consisted of sequential selections of all 7 targets in a full ring, resulting in a total of 7 selections per trial. The starting position for the trial was the first lit sphere, meaning that the measured distances were always between two target spheres. Since the distances between the spheres were the same, this ensured the selections were valid for the computation of the ID. The subjects were instructed to select the targets as quickly and accurately as possible, as it is common in most Fitts' Law experiments [DKK07, MMD<sup>+</sup>87, MI08].

While selecting a target correctly, subjects received visual feedback by changing the color of that target sphere from blue to green. Like previous studies on mid-air-selection [BSS13a, BSS13b], the subjects had

to confirm each selection by pressing a button on the keypad with their non-dominant hand to avoid any jitter caused by pressing buttons with their dominant hand.

We computed the distance of the position of the index finger to the sphere center, which indicated a selection if the distance was less than the radius of the target sphere. If subjects performed a selection while the target sphere was not highlighted green, we recorded this as a selection error and advanced the trial state. The dependent variables were movement time, error distance (deviation from target center), error rate (percentage of targets missed), and effective throughput (see Section 2).

With the calibrated position of the user's elbow, we defined 3 *interaction positions* (rings) in front of the user, as illustrated in Figure 5. The regions are reachable without moving the elbow rested on a table. Also previous studies indicate that regions close to the user's eyes offer increased performance over far regions [LBS14]. Also, according to the previous studies, the positions with elbow flexion are comfortable and divide the interaction space for the hand. Positions further away from the nondominant hand, i.e. taking into account Figure 5, the other side, would force the participant to either move their elbow, which would complicate further selections, or twist their arm, which we ruled out. The positions are the same for both conditions. To ensure equal distances between the elbow and the target spheres, we rotated the ring of spheres accordingly. Only one of the sphere rings in Figure 5 is visible at a time.

Additionally to the main experiment metrics, we asked subjects to complete subjective questionnaires. Before and after the experiment subjects were asked to complete a Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [KLBL93]. After the experimental phase subjects were asked to complete a Slater-Usch-Steed (SUS) presence questionnaire [UCAS00]. Moreover, the subjects had to judge their level of comfort after each condition (comfortable or uncomfortable).

#### 4.4 Hypotheses

Based on previous findings discussed in Section 2, we evaluate the following three hypotheses:

H1: The performance measured by throughput is higher in a comfortable pose with an arm rest.

H2: The number of selection errors is lower in a comfortable pose with an arm rest.

H3: The subjective comfort level is higher when the subjects can rest their arm during selection tasks.

## 5 Results and Discussion

In the following section we summarize the results from the experiment. Results from the subjects were normally distributed according to a Shapiro-Wilk test at the 5% level. We analyzed the results with a repeated measure ANOVA and Tukey multiple comparisons at the 5% significance level. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity when Mauchly's test indicated that the assumption of sphericity had been violated.

### 5.1 Selection Performance

In this section we describe the analysis of the Fitts' Law selection performance of our experiment. In particular, we analyze the movement time between subsequent selections, rate of missed targets, error distances to target centers, and effective throughput. The effective throughput metric incorporates both the results for speed and accuracy to form an estimate of the bottom-line performance.

**Error Distance** The results for error distances between the center of each sphere and the finger position during selections are shown in Figure 6(a). As expected by Fitts' Law, the results show that the error distance for the two sphere distances significantly differs ( $F(1, 11)=6.116, p<.05, \eta_p^2=.357$ ). As expected, the sphere radius had a significant effect on the error distance ( $F(1, 11)=212.734, p<.001, \eta_p^2=.951$ ).

The average error distance during the experiment was  $M=7.556\text{mm}$  ( $SD=1.603\text{mm}$ ). For the comfortable condition the average was  $M=7.497\text{mm}$  ( $SD=1.596\text{mm}$ ), which was lower than for the uncomfortable condition ( $M=7.613\text{mm}, SD=1.614\text{mm}$ ).

For the small sphere distance the average error distance  $M=7.485\text{mm}$  ( $SD=1.164\text{mm}$ ) was significantly lower than the error distance for the large sphere distance  $M=7.626\text{mm}$  ( $SD=1.565\text{mm}$ ).

For the small sphere radius the average error distance  $M=6.351\text{mm}$  ( $SD=.997\text{mm}$ ) was significantly lower than the error distance for the large sphere radius  $M=8.760\text{mm}$  ( $SD=1.115\text{mm}$ ).

The results show an interaction effect of position and distance ( $F(1.324, 14.564)=5.223, p<.05, \eta_p^2=.322$ ) and of position, distance and radius ( $F(2, 22)=4.22, p<.05, \eta_p^2=.277$ ). We found no significant main effect of position ( $F(2, 22)=.931, p=.449, \eta_p^2=.07$ ) on error distance. Furthermore, we could not find any significant effect of comfort ( $F(1, 11)=.251, p=.626, \eta_p^2=.022$ ) on error distance.

Finally, an Independent Samples T-Test resulted in no significant difference in error distance between left and right handed subjects ( $p=.934$ ).

**Error Rate** The results for error rate are shown in Figure 6(b). The results show that the error rate for the two sphere distances significantly differs ( $F(1, 11)=9.009, p<.05, \eta_p^2=.45$ ). As expected, also the radius had a significant effect on the error rate ( $F(1, 11)=26.224, p<.001, \eta_p^2=.705$ ).

The average error rate during the experiment was  $M=6.94\%$  ( $SD=7.34\%$ ). For the comfortable condition the average was  $M=6.07\%$  ( $SD=6.13\%$ ) lower than the average for the uncomfortable condition which as  $M=7.81\%$  ( $SD=8.31\%$ ).

We measured a significantly lower average error rate  $M=6.31\%$  ( $SD=7.63\%$ ) for the small sphere distance compared to the large sphere distance ( $M=7.58\%, SD=7.01\%$ ).

As expected, for the small sphere radius the average error rate  $M=9.22\%$  ( $SD=8.56\%$ ) was significantly higher than for the large sphere radius ( $M=4.66\%, SD=4.93\%$ ).

We found an interaction effect of comfort and position ( $F(2, 22)=6.794, p<.05, \eta_p^2=.382$ ) and the results show an interaction effect of position, distance and radius ( $F(2, 22)=5.683, p<.05, \eta_p^2=.341$ ). However, we found no significant main effect of the position ( $F(2, 22)=1.242, p=.308, \eta_p^2=.101$ ) on the error rate, or of the comfort on the error rate ( $F(1, 11)=1.646, p=.226, \eta_p^2=.130$ ).

Finally, an Independent Samples T-Test revealed a significant difference in error rate between left and right handed subjects ( $p<.05$ ). The mean error rate for left handed subjects ( $M=8.89\%, SD=7.54\%$ ) was significantly higher than the error rate of right handed subjects ( $M=6.55\%, SD=7.25\%$ ).

**Effective Throughput** The results for the effective throughput are shown in Figure 6(c). We found a significant main effect of comfort ( $F(1, 11)=6.157, p<.05, \eta_p^2=.359$ ) on throughput. Additionally, we

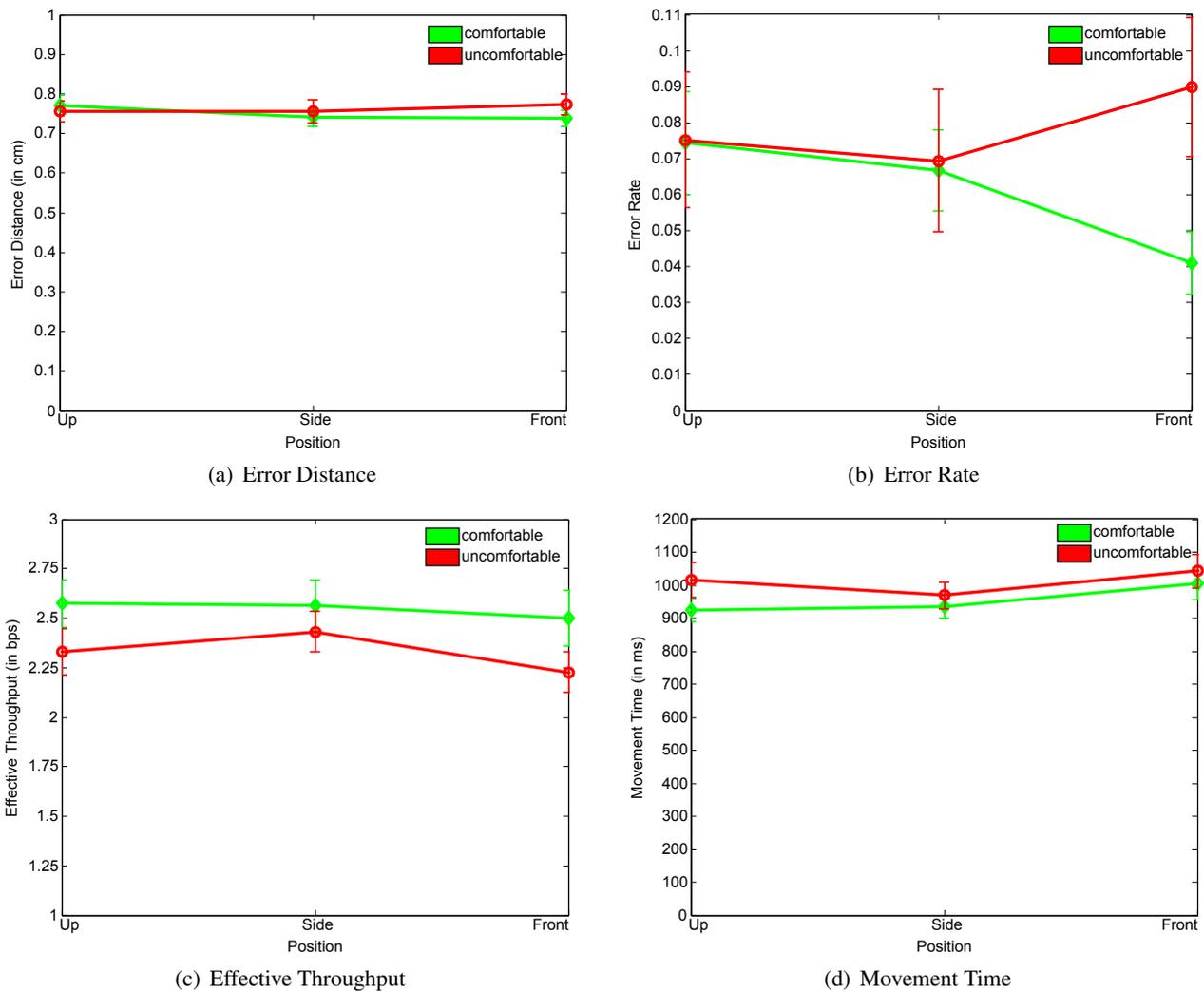


Figure 6: Plots of the experiment’s results. The x-axis show the interaction positions and the y-axis the a) error distances in cm, b) error rate, c) effective throughput in bits per second (bps) and d) the movement time in ms. The green lines show the comfortable pose. The red lines show the uncomfortable pose

found a significant main effect of sphere radius ( $F(1, 11)=8.065, p<.05, \eta_p^2=.423$ ) on throughput.

The average throughput during the experiment was  $M=2.44$ bps ( $SD=.47$ bps). Also, the average throughput for the comfortable condition  $M=2.55$ bps ( $SD=.49$ bps) was significantly higher than for the uncomfortable condition  $M=2.33$ bps ( $SD=.43$ bps). For the small sphere radius the average with  $M=2.378$ bps ( $SD=.103$ bps) was lower than for big sphere radius  $M=2.498$ bps ( $SD=.105$ bps).

The results show no significant effect of the three positions ( $F(1.38, 15.176)=2.157, p=.159, \eta_p^2=.164$ ) on throughput. Also we found no significant effect of the sphere distance ( $F(1, 11)=4.078, p=.068, \eta_p^2=.270$ ) on the effective throughput.

Furthermore, we found a significant interaction ef-

fect between position and distance ( $F(2, 22)=4.795, p<.05, \eta_p^2=.304$ ). An Independent Samples T-Test revealed no significant difference in effective throughput between left and right handed subjects ( $p=.887$ ).

**Movement Time** The results for the movement time are shown in Figure 6(d). We found a significant main effect of position ( $F(2, 22)=4.117, p<.05, \eta_p^2=.272$ ) on movement time. As expected, the movement time for the two distances differs significantly ( $F(1, 11)=152.64, p<.001, \eta_p^2=.933$ ) and also the radius had a significant effect on the movement time ( $F(1, 11)=60.72, p<.001, \eta_p^2=.847$ ).

The average movement time during the experiment was  $M=982$ ms ( $SD=205$ ms). For the comfortable condition the average movement time  $M=955$ ms

(SD=194ms) was shorter than for the uncomfortable condition, for which it was M=1010ms (SD=212ms).

As expected, for the small distance the movement time M=903ms (SD=164ms) was significantly faster than for the large distance M=1061ms (SD=212ms).

Also, the mean movement time for the small sphere radius M=1061ms (SD=210ms) was slower than for the large sphere radius M=904ms (SD=166ms).

Post-hoc tests revealed that the movement time was significantly lower when the target was displayed at the Side position, compared to the Front position ( $p < .05$ ). However, we found no significance between the Side and Up ( $p = 0.481$ ) or the Front and Up ( $p = .096$ ) conditions. We found a significant interaction effect between position and radius ( $F(2, 22) = 4.904, p < .05, \eta_p^2 = .308$ ) and distance and radius ( $F(2, 22) = 14.24, p < .05, \eta_p^2 = .564$ ). An Independent Samples T-Test revealed no significant difference in movement time between left and right handed subjects ( $p = .172$ ).

### 5.2 Modeling

Fitts' Law can be used as a predictive model by regressing movement time on index of difficulty. The regression lines for movement time are presented in Figure 7. The predictive quality of the model, as expressed by  $\chi^2$  values (.12, .27), is very high for both the comfortable and uncomfortable condition.

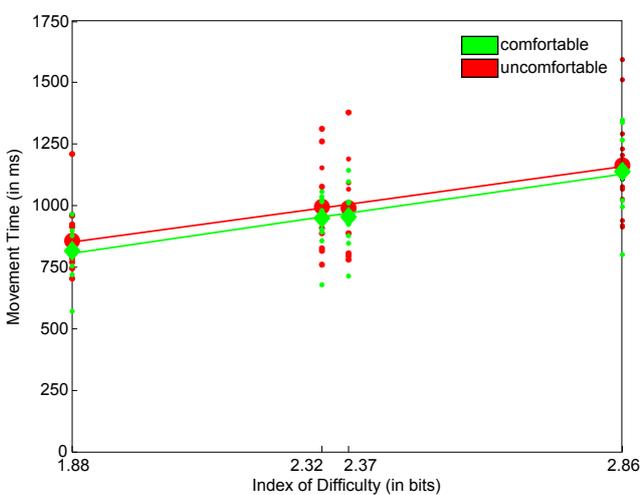


Figure 7: Models for the selection: The lines show the regressions of the measured movement time for the comfortable (green) and uncomfortable (red) pose.

### 5.3 Questionnaires

Before and after the experiment, we asked subjects to judge their level of simulator sickness as well as their subjective sense of presence. While we measured an average pre-SSQ score of M=8.10 (SD=9.14), the post-SSQ score was M=13.09 (SD=13.29). We found no significant effect of the increase in simulator sickness over the time of the experiment ( $t(11) = -1.71, p = .116$ ). The mean SUS-score for the reported sense of feeling present in the virtual scene was M=3.65 (SD=.82), which indicates a reasonably high level of presence.

Besides the SSQ, we asked subjects to judge their subjective level of postural comfort during the experiment by giving subjective values on a scale of 0 (uncomfortable) to 1 (comfortable). We analyzed these subjective comfort levels, as shown in Figure 8. The plot shows the subjective comfort levels before (pre) and after (post) the condition was tested. It shows a lower average in the condition without an arm rest (uncomfortable). Taking into account the participants comment, that the table was hard and uncomfortable, the outlier can be explained. Paired T-Tests show no significant change of subjective comfort in the condition with an arm rest (comfortable) ( $t(11) = .238$ ,

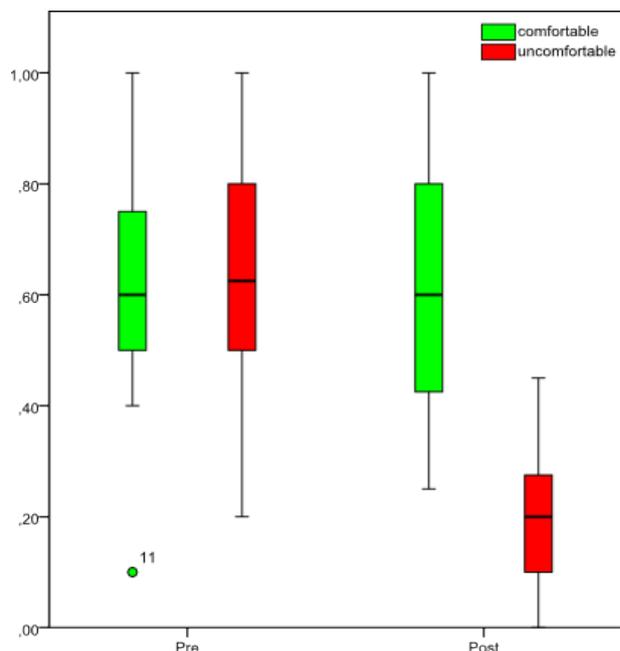


Figure 8: Boxplots showing the subjective comfort level before (pre) and after (post) the condition: the green bars show the comfortable condition, the red bars show the uncomfortable condition.

$p=.817$ ). However, a Paired T-Test for the uncomfortable condition shows a significant decrease of subjective comfort ( $t(11)=4.343$ ,  $p<.05$ ). We compared the measured subjective comfort of both conditions before the respective trials (pre) using an Independent Samples T-Test and found no significant difference ( $t(22)=.299$ ,  $p=.768$ ). However, the Independent Samples T-Test for the comfort levels after the condition was tested (post) shows a significant difference between the subjective comfort ( $t(22)=5.367$ ,  $p<.001$ ).

## 5.4 Discussion

The results of the Fitts' Law experiment revealed the importance of comfort for 3D user interfaces. Offering subjects means to comfortably rest their arm, or specifically their elbow, allows them to efficiently utilize 3D user interfaces in an IVE. The significantly increased throughput with an arm rest clearly indicates a significant improvement over the free mid-air interaction. This confirms our hypothesis H1.

Additionally, since comfort is very subjective, the evaluation of the subjective estimation of the participants' comfort level showed that the condition with the arm rest was preferable to the condition without. While at the beginning of the trials we could not find a significant difference between the conditions, by the end of the trial the difference was significant. This supports our hypothesis H3. Another interesting note is that, as Figure 8 indicates, some subjects judged an increase of comfort over the course of the experiment in the comfortable condition. Some subjects informally noted that they were not used to the pose at first, but got used to it quickly. Also, several subjects left comments such as, "Resting my arm helped a lot!"

However, the results show that, contrary to H2, the comfortable pose with an arm rest did not have a significant influence on the error rate. This could be due to the limited precision a finger offers during manual selection due to hand jitter. Another limiting aspect might be the low resolution of the utilized Oculus Rift HMD. Future work could evaluate higher resolution HMDs to determine whether low resolution was a factor limiting the influence of comfort. However, while we conducted our studies in a fully IVE, as previous studies concerning fatigue suggest [Sha98], our results are most likely valid for semi-immersive VR setups. The main difference to those setups is the visualization. However, in such setups, the user's

hands always occlude virtual objects and the vergence-accommodation conflict arises, which might cause further problems.

While we found different interaction effects for the different performance metrics related to Fitts' Law, we also found an interaction effect between comfort and position for the error rate. We measured fewer errors in the comfortable condition for the front position than in the uncomfortable condition and positions. Additionally, we found an interaction effect of position and distance on error distance and throughput, which may be explained by the effects of depth perception in VR during selection tasks [LBS14].

In future work we plan to extend our approach to 3D manipulation tasks. However, since Fitts' Law was designed to model selection task performance only, different models have to be used to evaluate the performance for manipulation tasks such as rotations, translations, scalings etc.

## 6 Conclusion and Future Work

In this article we investigated the importance of comfort for the performance in 3D user interfaces. We first summarized the pre-study which determined which regions are considered comfortable when interacting in mid-air while standing. Based on the results, we decided to analyze a more comfortable body poses for the interaction. In particular, we analyzed the influence of a comfortable arm rest on performance in immersive desktop setups. While many Science Fiction movies and novels envision a plethora of vivid virtual systems which demand that the user stands within them to navigate and control the system while moving utilizing their whole arms, prolonged use of such systems turns out to be immensely tasking for the user. To permit users to experience the immersive experience such systems potentially offer without the negative aspects, we evaluated possibilities to increase the comfort. One such choice would be to allow users to rest their arm and to seat them in something similar to common desktop workspaces. For many application scenarios, for instance, when navigation is not required, this pose has the potential to be beneficial. The conducted Fitts' Law experiment yielded interesting results for such immersive desktop setups. To our knowledge, our experiment is one of the first studies, which showed that comfort has a significant effect on effective throughput according to Fitts' Law in IVEs. Despite the high immersion of modern HMDs, it is

necessary to carefully design the real environment to the user's comfort.

These results offer interesting guidelines for future 3D user interfaces in immersive desktop setups:

G1: If it is possible to use an elbow rest, make use of *elbow-centered 3DUI menus*, characterized by elements that are optimally reachable along a partial sphere centered around the elbow rest without the necessity to lift the arm.

G2: Along the elbow-centered partial sphere, menu elements should be displayed in decreasing order of importance from the head position, i.e. the most important elements should be displayed close to the eyes whereas the least important objects should be displayed towards the far end of the partial sphere (cf. [LBS14]).

Following these guidelines, future work could evaluate the effectiveness of established navigation and selection techniques adapted to the immersive desktop setup. Even novel input or haptic feedback devices, included in an armrest, could be developed which could further increase the level of immersion in virtual environments.

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