Visual Blur in Immersive Virtual Environments: Does Depth of Field or Motion Blur Affect Distance and Speed Estimation?

Eike Langbehn[*] Tino Raupp[†] Gerd Bruder[‡] Frank Steinicke[§]
Human-Computer Interaction
University of Hamburg

Benjamin Bolte[¶] Markus Lappe[||]
Institute for Psychology
University of Muenster

Abstract

It is known for decades that users tend to significantly underestimate or overestimate distances or speed in immersive virtual environments (IVEs) compared to corresponding judgments in the real world. Although several factors have been identified in the past that could explain small portions of this effect, the main causes of these perceptual discrepancies still remain elusive. One of the factors that has received less attention in the literature is the amount of blur presented in the visual imagery, for example, when using a head-mounted display (HMD).

In this paper, we analyze the impact of the visual blur effects depth-of-field and motion blur in terms of their effects on distance and speed estimation in IVEs. We conducted three psychophysical experiments in which we compared distance or speed estimation between the real world and IVEs with different levels of depth-of-field or motion blur. Our results indicate that the amount of blur added to the visual stimuli had no noticeable influence on distance and speed estimation even when high magnitudes of blur were shown. Our findings suggest that the human perceptual system is highly capable of extracting depth and motion information regardless of blur, and implies that blur can likely be ruled out as the main cause of these misperception effects in IVEs.

Keywords: Virtual Environments; Distance and Speed Estimation; Visual Blur

Concepts: •**Human-centered computing** → **Virtual reality;** •**Computing methodologies** → *Perception; Virtual reality;*

1 Introduction

Accurate distance and speed estimation is necessary for many activities in the real world such as locomotion and navigation. Since more and more of such activities are transferred to virtual environments (VEs) in domains like architecture, simulation and training, it is becoming increasingly important for practitioners to develop systems in which users perceive spatial properties such as distances, sizes or speed in an accurate way, or at least match the perceptual quality as arising in similar situations in the real world. However, while humans are quite accurate when estimating distances in the real world [Rieser et al. 1990], in VEs such spatial judgments tend to significantly differ from the real world, i. e., often they are less precise and accurate with a large bias to underestimate distances in vista space [Loomis and Knapp 2003; Witmer and Kline 1998].

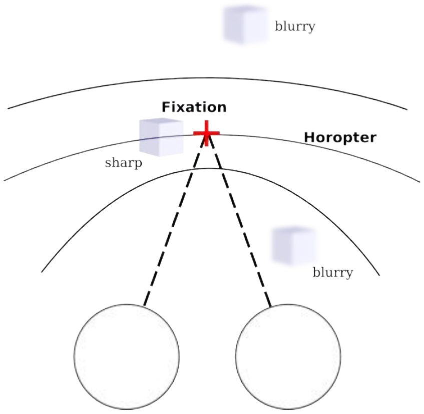

Figure 1: *Objects can be fused and appear sharply only if their distance matches panum's fusional area around the horopter defined by the fixation point of the observer's eyes.*

The perception of distances and speed involves the integration of different cues that are extracted from the visual sense and body senses. While previous research has focused on analyzing different factors for their effect on spatial judgments in VEs [Renner et al. 2013], one factor has received less attention in the published literature: *visual blur* [Palmer 1999; Held et al. 2010].

There are several situations where visual blur is involved when using head-mounted displays (HMDs):

- When humans focus on an object in the real world, the eyes verge towards it to bring it into the fovea, while they also accommodate to the distance of the object to bring it into sharp focus on the retina. Assuming that a user has 20/20 visual acuity in the real world, this is usually reduced in HMDs due to the lower pixel resolution or caused by only partial accommodation responses in the scope of the accommodation-convergence conflict [Palmer 1999]. Or, in other words, the entire virtual world appears slightly blurred compared to what one would see in a similar situation in the real world.
- When fixating on an object in the real world, the power of the lenses in the eyes is changed such that objects at the same or similar distances within a region around the horopter [Palmer 1999] appear sharply throughout the visual field, whereas objects that have a smaller or larger distance from the eyes appear increasingly blurred (see Figure 1). Most current-state HMDs are not able to naturally replicate this effect in VEs, with a few exceptions based on light-field technologies

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[*] e-mail:eike.langbehn@uni-hamburg.de
[†] e-mail:tino.raupp@studium.uni-hamburg.de
[‡] e-mail:gerd.bruder@uni-hamburg.de
[§] e-mail:frank.steinicke@uni-hamburg.de
[¶] e-mail:accounts@boltenet.de
[||] e-mail:mlappe@uni-muenster.de

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[Lanman and Luebke 2013]. However, assuming that the fixation point of the user's eyes is known or tracked, it is possible to induce similar visual blur in the computer-graphically generated visual imagery that is shown on the HMD by using depth-of-field effects [Carnegie and Rhee 2015]. Since most HMDs do not come with an integrated eye tracker, VEs are usually not presented with (perceptually accurate) depth-of-field effects.

- Furthermore, due to the limited refresh rate of current HMDs, the natural amount of optic flow present during movements in the real world is reduced, which is often counteracted by using another visual effects technique called motion blur [Potmesil and Chakravarty 1983].

Hence, there are multiple differences between the real world and HMDs in terms of the amount of blur present which either increase or reduce blur compared to natural viewing. In this paper, we present three experiments, in which we investigate whether visual blur has a noticeable effect on distance and speed estimation, and also to understand how much of the perceptual discrepancies between real and virtual worlds might be explained by visual blur. Although, with the current state of HMD hardware technologies it is not possible to test perceptual effects without any of the above outlined blur differences, we separately analyzed depth-of-field (DOF) and motion blur with different levels of magnitude and measured their impact on distance and speed estimation, respectively.

This paper is structured as follows: Section 2 presents related work in this field. Sections 3, 4, and 5 describe the psychophysical experiments that we conducted to analyze three different effects of visual blur, i. e., effects on distance estimation with and without varying focus as well as speed estimation. The results are discussed in Section 6. Section 7 concludes the paper.

2 Related Work

During walking in the real world, accurate estimations of distances and self-motion speed are essential, e. g., to minimize collisions, reach high navigation performance, or build up an accurate mental map of an environment. Depth perception is based on the integration and interpretation of available depth cues including binocular disparity and convergence, accommodative focus, linear perspective, aerial perspective, occlusion, shading, and motion parallax [Howard and Rogers 2002]. However, much empirical evidence has been collected over the last decade which indicates that distance and speed perception in VEs differ significantly from the real world, with very close distances often being overestimated while distances in vista space tend to be underestimated [Rolland et al. 1995; Rousset et al. 2015; Bruder et al. 2015; Creem-Regehr et al. 2005; Willemsen et al. 2008; Li et al. 2015; Creem-Regehr et al. 2015]. Renner et al. [2013] reviewed the extensive literature on distance perception in VEs.

Several theories and approaches to improve spatial perception in VEs have been presented. For instance, some researchers believe that feedback during interaction might be sufficient for the highly adaptable human perceptual system to reduce differences in spatial judgments given sufficient time [Richardson and Waller 2007]. Other researchers believe that the sense of presence in VEs has a direct effect on the quality of spatial judgments [Interrante et al. 2007], such that low fidelity virtual worlds might indirectly impair spatial judgments [Thompson et al. 2004; Phillips et al. 2012; Ahmed et al. 2010]. In contrast, presenting a richer and more realistic virtual world using high quality graphics might improve distance estimation in VEs [Renner et al. 2013]. Psychophysical experiments revealed significant differences when estimating distances in non-photorealistic versus high fidelity VEs [Phillips et al. 2009; Naceri et al. 2011]. Another finding supporting this theory is that image resolution seemed to influence perception of distance as well [Ryu et al. 2005].

Another potential explanation of where the misinterpretation might originate is based on incorrect depth cues provided to the human eye when looking through an HMD, such as the accommodation-convergence conflict [Hoffman et al. 2008]. When focusing on an object in the real world, the human eye adjusts the ciliary muscles to bring the object into sharp focus on the retina, whereas the shape of the lens causes objects at different distances behind or in front of it to appear blurred (see Figure 1). However, with current-state HMD designs, independently of where and on which the eyes of the observer are focused, every object in the visual field appears sharply. Hence, to provide a similar viewing experience as in the real world, researchers proposed to add artificial blur to the visual imagery [Carnegie and Rhee 2015; Hillaire et al. 2007]. In particular, Held et al. [2010] found that visual blur plays a significant role in perceiving size and distance, at least in non-stereoscopic images. They presented a probabilistic model based on Bayes' Law to explain how blur combined with perspective cues can be exploited to estimate absolute egocentric distances to objects in static images viewed on a CRT monitor. Blur effects like DOF are also known to mitigate the accommodation-convergence conflict in HMDs and therefore help to reduce visual discomfort like eye fatigue, headaches and nausea [Carnegie and Rhee 2015]. Moehring et al. [2009] state that DOF blur in HMD environments might additionally improve spatial perception.

In contrast, distance estimation in the real world is not affected by visual blur [Legge et al. 2016; Tarampi et al. 2010]. At least, when the whole field of view is blurred, e. g., as people with impaired vision.

Research on speed perception in HMD environments indicate a general tendency to underestimate self-motion speed as well [Nilsson et al. 2015]. Banton et al. [2005] state that this might originate from the small field of view (FOV) of HMDs which does not reach into the far periphery of the eyes [Jones et al. 2013]. In particular, they assume that lamellar flow is necessary for a correct speed perception and that this cue is cut off by a limited FOV because the user can not see the ground while looking straight ahead. They found a significant effect showing that the display's FOV was inversely proportional to the underestimation of walking speed in a VE, while speed estimation was more accurate when participants perceived lamellar flow [Nilsson et al. 2014]. Furthermore, motion blur has been suggested to improve speed estimation. Several studies have shown that humans are generally able to gain information about the direction and speed of moving from motion blur [Burr and Ross 2002; Francis and Kim 2001; Ross 2004]. Furthermore, Kim and Francis [1998] showed that motion lines have the potential to change motion perception as well. In general, research on speed estimation in VEs as compared to the extensive literature on distance estimation is still underrepresented in this field of research.

3 Experiment E1: Distance Estimation

In this section we describe the psychophysical experiment in which we analyzed distance estimation in real and virtual environments using an HMD while different levels of DOF blur were compared.

3.1 Participants

20 participants (2 female and 18 male, ages $19-36$, $M = 27.2$) completed the experiment. The participants were students or members of the local department of informatics, who obtained class credit for their participation. All of our participants had normal

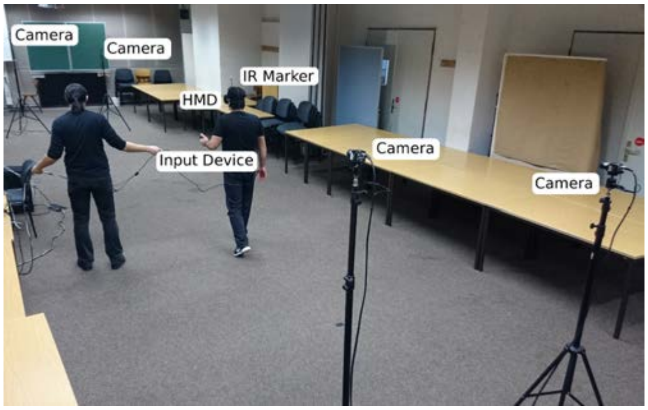

Figure 2: *Photo with annotations showing a participant and an experimenter walking in the laboratory space.*

or corrected-to-normal vision. Eight participants wore glasses and two participants wore contact lenses during the experiment. None of our participants reported a disorder of equilibrium. One of our participants reported an artificial lens in his left eye. No other vision disorders have been reported by our participants. 11 participants had participated in an experiment involving HMDs before. The experience of the participants with 3D stereoscopic displays (cinema, games etc.) in a range of 1 (no experience) to 5 (lots of experience) was $M = 3.5$ ($SD = 1.27$). Most of them had experiences with 3D computer games ($M = 3.45$, $SD = 1.6$, in a range of 1 = no experience to 5 = lots of experience) and they usually played 6.65 hours per week on average ($SD = 8.84$). We measured the interpupillary distances (IPDs) of our participants before the experiment using the built-in measurement process of the Oculus Rift configuration utility. The IPDs of our participants ranged between $6.2-6.9$cm ($M = 6.5$cm, $SD = .2$cm). We used the IPD of each participant to provide a correct perspective and stereoscopic rendering on the HMD. The body height of the participants varied between $1.60-1.90$m ($M = 1.79$m, $SD = .07$m). The total time per participant, including pre-questionnaires, instructions, experiment, breaks, post-questionnaires, and debriefing, was 30 minutes. Participants wore the HMD for approximately $20-25$ minutes. They were allowed to take breaks at any time between trials.

3.2 Materials

The experiment took place in a sealed-off empty seminar room (see Figure 2). We instructed the participants to wear an Oculus Rift DK2 HMD, which provides a resolution of 960×1080 pixels per eye with an approximately 110° diagonal field of view. Positional tracking was done with a WorldViz PPT tracking system that consisted of four cameras, one in each corner of the room, and an infrared LED marker at the participant's head. The tracking system sent the position data via VRPN and a local network to the rendering computer. During the experiment the room was darkened in order to reduce the participant's perception of the real world. The participants received instructions on slides presented on the HMD. A Gyration Air Mouse GO Plus served as an input device via which the participants provided responses during the experiment. For rendering, system control and logging we used an Intel computer with 3.5GHz Core i7 processor, 32GB of main memory and an Nvidia Geforce GTX 980 graphics card.

Figure 3: *The focus point in this condition is 5m in front of the participant. The top picture shows the environment without blur, the picture in the middle provides low blur and the bottom one shows high blur.*

The virtual environment was rendered using the Unreal Engine 4 and showed a natural forest scene and a straight path in front of the participant (see Figure 3). We chose this environment because blur effects are much more visible in a high fidelity visually rich scene than in an abstract reduced-cue scene. As commonly done when using the blind walking method to assess distance perception in HMD environments we displayed a red target on the path at a computer-controlled distance. In some of the experimental conditions, we applied a perceptually-inspired depth-of-field post-processing shader in the Unreal Engine that showed everything at the focused distance sharply, but blurred the rest of the scene. For this, we used the built-in BokehDOF effect (MaxBokehSize = 1.5, NearTransitionRegion = 200, FarTransitionRegion = 200, FocalRegion = 200) with a scale of 0.5 or 1.0, respectively (low blur and high blur). The focused distance of the shader matched the distance to the red target. The participants were instructed to maintain a focus on this target, which we found worked well to control the focused distance without the need for an eye tracking device to observe the participant's eyes and adjust the focus.

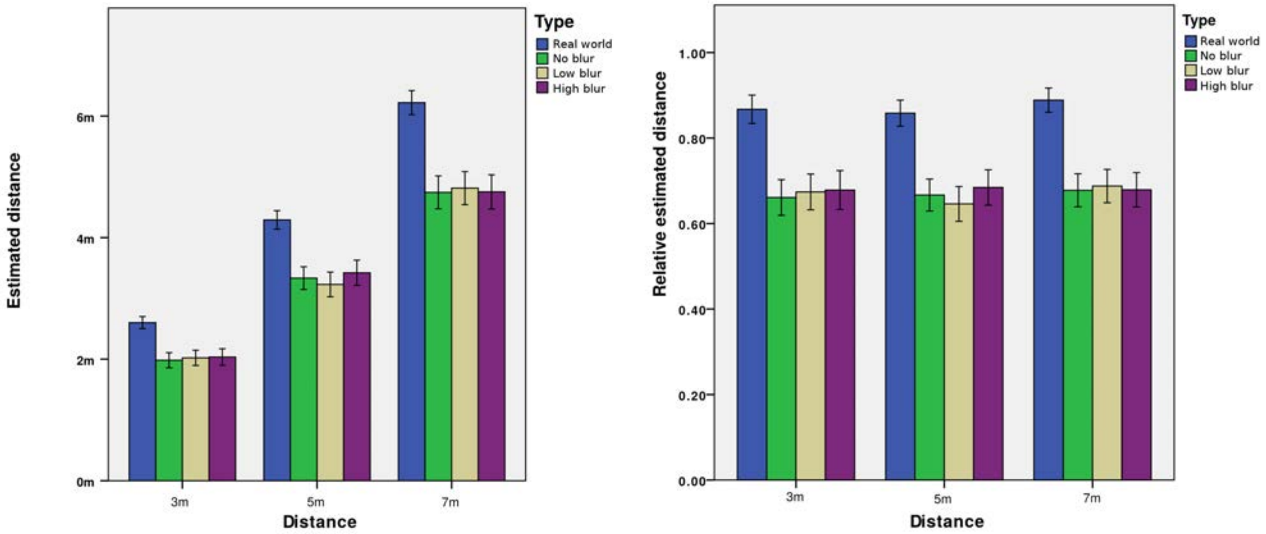

Figure 4: *Pooled results of the distance estimation experiment for the different visual blur conditions: (left) absolute and (right) relative. The vertical bars indicate the standard error.*

3.3 Methods

We used a 4×3 full-factorial within-subjects experimental design. We tested 4 blur conditions (real environment, virtual environment without blur, with low blur and with high blur) and 3 distance conditions (3m, 5m and 7m in front of the participant). The low blur condition was chosen to closely approximate a "real" blur when focusing on an object. This was configured by a subjective estimation of the experimenters according to a similar real-world situation. Figure 3 illustrates the conditions.

The baseline conditions in the real environment were tested in a block at the beginning of the experiment, followed by the conditions in the virtual environment. The conditions were randomized but uniformly distributed within the blocks. The positions at which the participant was located in the virtual world were randomized between trials. In order to assess the perceived distance to the red target we used the active response method of blind walking [Witmer and Sadowski 1998]. Using this method, the participants had to look at the red target marker or a laser pointer mark at the given distance in the virtual or real environment, respectively. After a few seconds, the participants clicked on the input device and the scene turned black. Now, without vision, they had to walk the distance to the target they had previously seen. In the conditions in the real world, we used a sleep mask to blindfold them. When the participants thought that they had reached the distance, they clicked again and we saved the walked distance by computing the Euclidean distance between the end point and the start point on the floor in two dimensions (cf. [Renner et al. 2013]). Then, still blindfolded, the participants were guided back to the start position with the help of the experimenter, and the next trial started.

3.4 Results

We analyzed the results with a repeated-measures ANOVA and TukeyHSD multiple comparisons at the 5% significance level. A Shapiro-Wilk test did not indicate that the assumption of normality had been violated. When Mauchly's test of sphericity indicated that the assumption of sphericity had been violated we used Greenhouse-Geisser estimates of sphericity to correct the degrees of freedom. We report statistics for both absolute and relative judgments in the following to achieve comparability for the two mainly used types of analyses in the distance estimation literature.

Figure 4 (left) shows the absolute values of the estimated distances and Figure 4 (right) the relative values. We found a significant main effect of the blur type on distance estimation for absolute values, $F(1.5, 28.4) = 39.67$, $p < .001$, $\eta_p^2 = .676$, and relative values, $F(1.4, 28.3) = 40.74$, $p < .001$, $\eta_p^2 = .682$. Post-hoc tests showed that the estimated distances between the real world condition and each of the conditions in the virtual world were significantly different ($p < .001$). We could not find any significant effect between the different blur types in the VE. The bayes factor for this was .061.

Furthermore, we found a significant main effect of the target distance on distance estimation for absolute values, $F(1.2, 22) = 330.13$, $p < .001$, $\eta_p^2 = .946$, but not for relative values, $F(1.25, 23.6) = .68$, $p = .45$, $\eta_p^2 = .034$. For relative values, we found a bayes factor of .062. Post-hoc tests showed that the estimated distances between each two target distances were significantly different ($p < .001$).

Moreover, we found a significant interaction effect between blur type and target distance on distance estimation for absolute values, $F(3.2, 61.5) = 7.35$, $p < .001$, $\eta_p^2 = .279$, but not for relative values, $F(6, 114) = .52$, $p = .8$, $\eta_p^2 = .026$. For relative values, we found a bayes factor of .003.

3.5 Discussion

It is an interesting result that our experiment did not reveal a significant effect on distance estimation of the even quite large amount of blur that we added with DOF to the visual stimulus. Additionally, the relatively small value of the bayes factor even suggests that it is likely that blur has no influence on distance estimation at all. In fact, the different blur conditions could only explain a very small part of the variance in the responses.

We believe that there are three potential explanations why we observed such small effect sizes and observed power in the blur conditions in the VE:

a) The tested distances were still in the range where convergence and motion parallax offer good distance cues, which might have dominated any effect from even large amounts of DOF blur. This might explain why related studies using monoscopic imagery have found an effect of blur on distance and size estimation [Held et al. 2010].

b) Despite our perceptual calibration, the types and strengths of blur that we tested in this experiment based on DOF visual effects might not have been interpreted as a depth cue by the human perceptual system due to slight differences in magnitude or distribution (cf. Bayesian cue integration [Ernst 2006]). We address this using a refined model in Section 5.

c) The resolution of the Oculus Rift DK2 HMD, which supports only 960×1080 pixels per eye, limited the visual acuity. A potential explanation might be that the additional amount of blur had no noticeable additional effect on distance estimation, but that less blur might have had an effect. However, we should note that this explanation would conflict with results of related studies, which found that higher resolution did not improve distance estimation (e. g., [Bruder et al. 2015]).

Furthermore, it is to take note of the fact, that we found a much higher underestimation in VE conditions than others who used similar hardware (e. g., [Creem-Regehr et al. 2015; Li et al. 2015]). This might be explained by slightly different tested distances, different VEs (indoor vs. outdoor) and different calibration. We measured and set the IPD of each participant individually while Creem-Regehr et al. set the IPD to $6.25cm$ for all participants. Additionally, we also set the height of the camera according to the height of the participants.

We also found a slight underestimation in the real world condition. Since we do not know what is the reason for this, we guess it is related to the construction of the room which had the form of a tube.

4 Experiment E2: Speed Estimation

In this section, we describe the psychophysical experiment in which we analyzed speed estimation with an HMD while different levels of motion blur were compared. The experiment was conducted together with Experiment E1, the same materials were used (see Sec. 3.2) and the same participants (see Sec. 3.1) completed the experiment. The order of the experiments was counterbalanced.

Instead of a red target on the ground and the depth-of-field shader in the scene in Experiment E1, we used a different method in which we showed a camera flight through the VE to the participants. We tested the effects of motion blur post-processing by using a shader (cf. [Tomura 31/08/2016]) that showed the focused point in the scene sharply and everything else blurry, similar to the (fast) motion of a movie camera. For this, we used following settings: RadiusExponent = 2, BlurRadius = 0.1, BlurAmount = 0.25, 0.5 or 0.75, respectively. In this experiment we decided against including a baseline condition in which we would usually test speed estimation in a real-world environment due to the fact that we are mainly interested in the relative differences between the different amounts of motion blur.

4.1 Methods

We used a 4×3 full-factorial within-subjects experimental design. We tested 4 blur conditions (without blur, with low blur, with medium blur and with high blur) and 3 velocity conditions (1m/s, 1.25m/s and 1.5m/s). Figure 5 illustrates the conditions. The conditions were presented randomly but uniformly distributed.

In order to assess the perceived walking speed we used a visual-proprioceptive perceptual matching method. Using this method, the participants had to stand on the start point in the real world and look forward while a camera flight through the VE with different levels of motion blur was shown. After the flight ended, the scene turned black. Now, without vision, they had to walk forward at the speed they had seen before. After the participants walked five meters, we saved the time they needed to walk this distance and calculated the mean speed. Then, still blindfolded, they had to walk back to the start position with the help of the experimenter, and the next trial started. The positions at which the participant was located in the VE were randomized between trials, so that participants could not use their position as a reference point.

4.2 Results

We analyzed the results with a repeated-measures ANOVA and TukeyHSD multiple comparisons at the 5% significance level. A

Figure 5: *Camera flight through the VE with no blur, low blur, medium blur and high blur from top to bottom, respectively.*

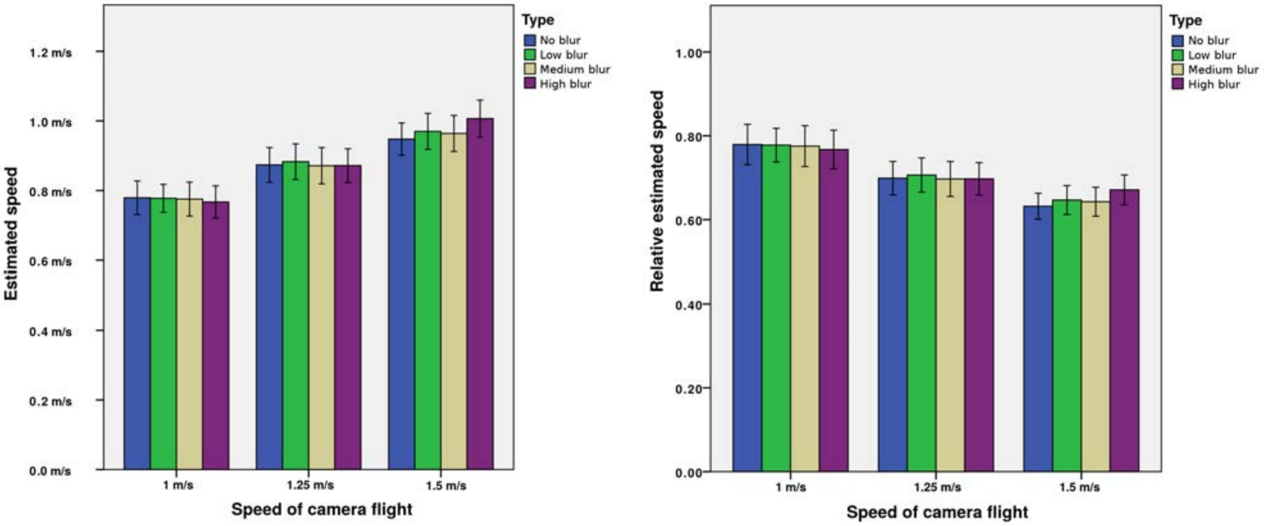

Figure 6: *Pooled results of the speed estimation experiment for the different motion blur conditions: (left) absolute and (right) relative. The vertical bars indicate the standard error.*

Shapiro-Wilk test did not indicate that the assumption of normality had been violated. When Mauchly's test of sphericity indicate that the assumption of sphericity had been violated we used Greenhouse-Geisser estimates of sphericity to correct the degrees of freedom. Again, we report statistics for both absolute and relative judgments.

Figure 6 (left) shows the absolute values of the estimated speeds and Figure 6 (right) the relative values. We found no significant effect of the blur type on speed estimation for absolute values, $F(3, 57) = .39$, $p = .76$, $\eta_p^2 = .02$, and relative values, $F(3, 57) = .2$, $p = .89$, $\eta_p^2 = .01$.

We found a significant main effect of the target speed on speed estimation for absolute values, $F(2, 38) = 70.05$, $p < .001$, $\eta_p^2 = .787$, and relative values, $F(1.53, 29) = 34.89$, $p < .001$, $\eta_p^2 = .647$. Post-hoc tests showed that the estimated speeds between each two target speeds were significantly different ($p \leq .001$).

Moreover, we found no significant interaction effect between blur type and target speed on speed estimation for absolute values, $F(6, 114) = .91$, $p = .49$, $\eta_p^2 = .046$, and relative values, $F(6, 114) = .67, p = .67, \eta_p^2 = .034$.

4.3 Discussion

As in Experiment E1 for distance estimation using DOF blur, our results in this second experiment showed no significant effect of the different motion blur conditions on speed estimation. Again, the effect sizes indicate that motion blur can only explain a very small part of the variance in the responses.

As for potential explanations of this effect, we believe that those discussed in Section 3.5 might also apply to motion blur. Moreover, most of the motion blur was visible in the periphery of the HMD, which, although it has a large field of view of 110° diagonally, might not be entirely the same as during real-world viewing, considering the human visual field spanning over about 200° horizontally into the far periphery of the eyes. Since the periphery of the eyes is highly sensitive to motion, an additional explanation might be that an even larger field of view of HMDs is required for this stimulation with blur to take effect [Nilsson et al. 2014].

5 Experiment E3: Distance Estimation with Varying Focus

As an extension to the previous experiments, in particular Experiment E1, we performed a psychophysical experiment with an improved DOF blur and a photorealistic replica model of the real laboratory in which we analyzed the effects of different focus points of the observer's eyes on distance estimation. In particular, we were interested in the effect of in focus vs. out of focus target objects on distance estimation. We had different participants in this experiment and slightly different materials.

5.1 Participants

15 participants (8 female and 7 male, ages $18-32$, $M = 23.5$) completed the experiment. The participants were students or members of the local departments of psychology, neuroscience, or computer science, who obtained class credit for their participation. All of our participants had normal or corrected-to-normal vision. Seven participants wore glasses and three participants wore contact lenses during the experiment. None of our participants reported a disorder of equilibrium. No other vision disorders have been reported by our participants. Four participants had participated in an experiment involving HMDs before. Eleven participants had much, one had moderate, and three had no 3D computer games experience. We measured the interpupillary distances (IPDs) of our participants before the experiment using a measuring tape. The IPDs of our participants ranged between $5.8 - 7.0$cm ($M = 6.3$cm, $SD = .3$cm). We used the IPD of each participant to provide a correct perspective and stereoscopic rendering on the HMD. The body height of the participants varied between $1.57 - 1.93$m ($M = 1.77$m, $SD = .11$m). The total time per participant, including pre-questionnaires, instructions, experiment, breaks, post-questionnaires, and debriefing, was 45 minutes. Participants wore the HMD for approximately $30 - 35$ minutes. They were allowed to take breaks at any time between trials.

5.2 Materials

The experiment took place in a sealed-off empty laboratory room. We instructed the participants to wear a Sensics zSight HMD, which provides a resolution of 1280×1024 pixels per eye with an approximately 60° diagonal field of view. Compared to the Oculus Rift DK 2 used in the previous experiments it provides a higher resolution but lower FOV. Positional tracking was done the same way as in the other experiments. For orientation tracking of the participant's head, we attached a wireless InertiaCube 3 orientation tracker from InterSense ($\leq 1^\circ$ accuracy, 4ms latency, 180Hz update rate) to the HMD. During the experiment the room was darkened and around the HMD was wapped a black cloth in order to reduce the participant's perception of the real world. The participants received instructions on slides presented on the HMD. A Nintendo Wii remote controller served as an input device via which the participants provided responses during the experiment. For rendering, system control and logging we used an Intel computer with 3.4GHz Core i7 processor, 16GB of main memory and an Nvidia Geforce GTX 680 graphics card.

The virtual environment was rendered using OpenGL 4.3 plus our own software and consisted of a photorealistic 3D replica of the real 10m × 7m laboratory room and the 3D replica of a real target pole (see Figure 7(top)). In some of the experimental conditions, we applied a perceptually-inspired depth-of-field post-processing shader that showed everything at the focused distance sharply, but blurred the rest of the scene. The focused distance of the shader matched the distance to the target pole (see Figure 7 (center)) or the back wall (see Figure 7 (bottom)) of the laboratory replica in focus.

In order to more closely mimic the DOF of the human eye, we created the DOF post-processing shaders based on the thin lens camera model as described in [Riguer et al. 2004]. Deviating from the described formula in [Riguer et al. 2004] to calculate the circle of confusion diameter (which, broadly speaking, represents the blur amount), we used the following formula from [Held et al. 2010]:

$$c = \left| A \frac{s_0}{z_0} \left(1 - \frac{1}{d} \right) \right|, \tag{1}$$

where we simulated the human eye using a lens to retina distance of $s_0 = 22$mm and a pupil diameter of $A = 4.6$mm (based on [Held et al. 2010]). The focus distance is given by z_0, which was set either to the distance between the participant and the target pole, or the distance between the participant and the back wall of the laboratory room. The relative distance between focus and object distance z_1 is denoted by $d = z_1/z_0$. In order to convert the metric into screen pixel units, we assumed that 1° visual angle covers .29mm on the retina [Palmer 1999]. We determined the final conversion factor by averaging the horizontal and vertical conversion factors, which were calculated based on the Sensics zSight horizontal (46.9°) and vertical (37.5°) FOV together with its pixel resolution. In addition, we used a blur filter kernel with 128 instead of the proposed 12 outer taps to increase the blur quality. The outer taps were aligned according to a Poisson disk distribution. To vary the blur strength, we applied a gain g to the circle of confusion diameter: $\hat{c} = |g|c$. When the gain was set to $g = 0$, no blur was thus applied to the scene. For a gain of $g = 1$, a blur mimicking the human eye was applied to the scene. Gains $g > 1$ increased the blur proportional to the simulated human eye blur. Finally, we used a 100 pixels maximum circle of confusion diameter to prevent blur artifacts.

5.3 Methods

We used a 3×3 full-factorial within-subjects experimental design. We tested 3 blur conditions (real environment, virtual environment with blur and target in focus, virtual environment with blur and target out of focus) and 3 distance conditions (3m, 5m and 7m in front of the participant).

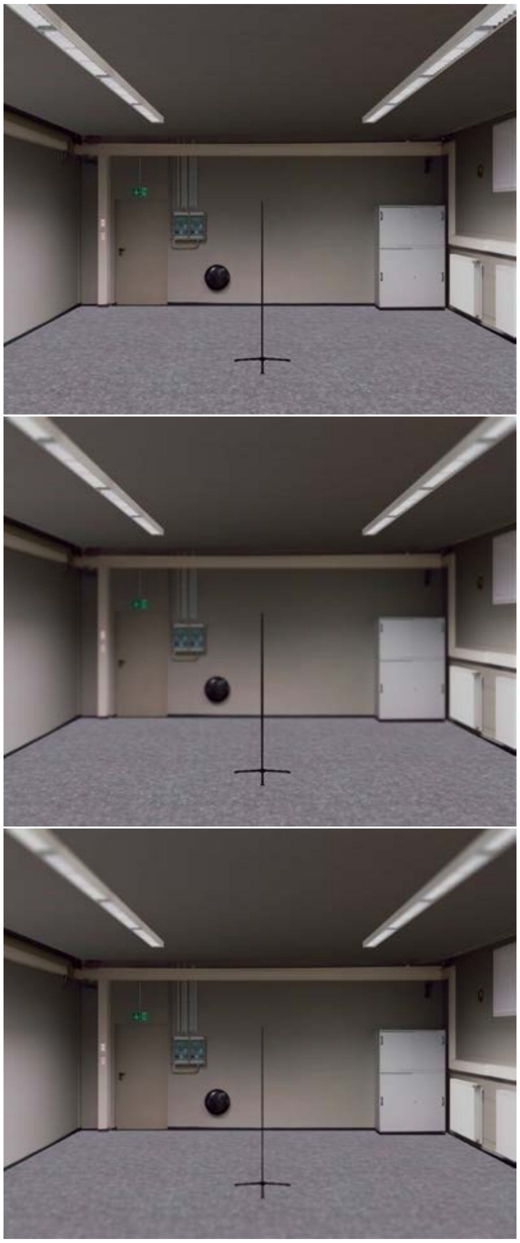

Figure 7: *Illustration of the visual stimuli for Experiment E3. The photorealistic laboratory room and target pole replica is shown (top) without and (center, bottom) with depth-of-field post-processing, respectively. The DOF post-processing focus is either (center) on the target pole or (bottom) on the back wall of the room.*

The baseline conditions in the real environment were tested in a block at the end of the experiment, after the conditions in the virtual environment. The conditions were randomized but uniformly distributed within the blocks. In the baseline block, we repeated each distance once yielding 3 trials in total. For the blur blocks, we performed 2 repetitions per distance. We additionally varied the blur intensities ($g = 0, 1, 2, 4, 8, 16$) to test its influence on participants' distance judgments. This means 6 (blur intensity) × 3 (target distance) × 2 (repetitions) $= 36$ trials in total were performed for each blur block. Within each block, all trials were presented in random order. Before each blur block, participants performed 3 training trials in total for a different set of distances (2m, 4m, 6m) and without blur. Participants started all trials from the same real and virtual position.

At the beginning of each trial, participants went to the trial start position and then orientated themselves to face the forward walking direction. Two markers on the HMD indicated the start and participant's position/orientation to support participants. A green rectangle appeared if position and orientation were within an acceptable tolerance (position: ±5cm, orientation: $\pm 4°$). Participants then pressed a button on the Nintendo Wii remote controller and the visual stimulus appeared (see Figure 7). According to our instructions, participants then looked at the target pole in order to estimate the distance towards it. Participants were instructed to look only at the target pole in the scene to control the focus of their eyes as good as possible without using an eye tracker. Following a button press on the Wii controller, the screen went black and participants had to walk to the target pole position without any visual stimulus. The next trial started after participants confirmed their final position by a button press on the Wii controller. We measured the Euclidean distance between the tracked infrared marker at the initial and final position of the participant. In the real world baseline condition, we used a real target pole instead of the 3D replica. After looking at the target pole, participants were blindfolded and the real target pole was put aside. Participants indicated their final position by standing on the spot. We subsequently measured the Euclidean distance between start and final position using a laser distance measurer.

5.4 Results

We analyzed the results with a repeated-measures ANOVA at the 5% significance level. A Shapiro-Wilk test did not indicate that the assumption of normality had been violated. When Mauchly's test of sphericity indicated that the assumption of sphericity had been violated we used Greenhouse-Geisser estimates of sphericity to correct the degrees of freedom. For the statistical analysis, we discarded all incomplete trials and trials in which participants accidentally pressed the Wii remote button before reaching the final position (3 of 1170 trials, $\leq .3\%$). We separately investigated the data for the target in focus and target out of focus conditions, as in real applications only one of the cases can occur at the same time. In contrast to the other experiments, we decided to just report relative judgments for this experiment because it simplified the comparison between different target distances since we have the focus condition additionally in this experiment.

Figure 8 (left) visualizes the experiment results at the participant level. For each participant, the mean relative estimated distance in percent is shown for varying blur strengths. The columns divide the data based on the target distances and the rows divide the data depending on whether the target was in focus or out of focus. Figure 8 (right) plots the same data at the group level, where participants' individual means are depicted as points. Error bars represent ±1 standard error.

In case of the target in focus condition, the two-way repeated-measures ANOVA revealed a significant main effect of the blur type, $F(1.63, 22.87) = 88.75$, $p < .001$, $\eta^2_G = .3194$. The main effect of target distance, $F(1.34, 18.80) = .76$, $p = .432$, $\eta^2_G = .0024$, and the interaction effect were not significant, $F(12, 168) = .79$, $p = .664$, $\eta^2_G = .0040$. Post-hoc tests showed that participants significantly underestimated distances for each virtual blur condition ($M_0 = 60.42\%, M_1 = 60.62\%, M_2 = 58.81\%, M_4 = 58.60\%, M_8 = 57.89\%, M_{16} = 60.07\%$) compared to the real-world baseline ($M_B = 92.57\%, p < .001$). All other comparisons were not significant using Holm family-wise error (FWE) correction. Without FWE correction, only the $g = 1$ and $g = 8$ blur types differed significantly ($p = .041$). The mean difference of estimated relative distances towards the target between no blur and the highest blur strength was $M = .34\%$ ($SD = 5.91\%$, $CI_{95} = [-2.93\%, 3.62\%]$, $t(14) = .22$, $p = .83$, $r = .06$). In addition, if the real-world baseline was excluded from the ANOVA, the main effect of target distance was no longer significant, $F(5, 70) = 2.15$, $p = .069$, $\eta^2_G = .0035$.

For the target out of focus condition, we found similar results. The main effect of blur type was significant, $F(1.52, 21.24) = 68.72$, $p < .001$, $\eta^2_G = .2768$, whereas the main effect of target distance, $F(1.15, 16.12) = .37$, $p = .579$, $\eta^2_G = .0015$, and the interaction effect were not significant, $F(12, 168) = 1.49$, $p = .131$, $\eta^2_G = .0066$. Participants significantly underestimated distances in each virtual blur condition ($M_0 = 61.45\%, M_1 = 60.07\%, M_2 = 61.39\%, M_4 = 61.23\%, M_8 = 59.52\%, M_{16} = 61.74\%$) compared to the real-world baseline ($M_B = 92.57\%, p < .001$), as revealed by post-hoc tests. All other comparisons were not significant with and without FWE correction. The mean difference of estimated relative distances between no blur and the highest blur strength was $M = -.28\%$ ($SD = 3.16\%$, $CI_{95} = [-2.04\%, 1.47\%]$, $t(14) = -.35$, $p = .73$, $r = .09$). The main effect of target distance was not significant if the real-world baseline was excluded from the ANOVA ($F(5, 70) = 1.45$, $p = .216$, $\eta^2_G = .0019$).

5.5 Discussion

Even with this revised experimental method and improved visual stimulus we found no evidence for an effect of DOF blur on distance estimation in IVEs, independently of whether the target was in focus or out of focus. The small mean differences between conditions together with the very low effect sizes (explaining $< .5\%$ of the variance) suggest that even if the effect would be statistically significant, it would be negligibly small. The results together with Experiment E1 (see Section 3) further support the notion that there is–if at all–a negligibly small effect of DOF blur on distance estimation.

6 General Discussion

In general, we can summarize our results as follows. It was not possible for us to find a significant effect of blur on distance or speed estimation in VEs. Especially, this was not possible under different conditions in three experiments:

- We tested different experiment designs and participants.
- We used different HMDs in the experiments.
- We used different visual stimuli. Experiments E1 and E2 used a visually rich and large outdoor environment and E3 used a replica indoor environment of the real lab room.
- We used different implementations of the blur shaders.
- We tested different blur levels and distances.
- We tested different blur foci.

Nevertheless, we found no influence of blur on distance or speed judgments. But since we tested 35 participants in carefully conducted scientific experiments, and could not find any significant effects of blur on distance and speed judgments, it is reasonable to assume that the statistical effect size of such blur effects on distance and speed underestimation or overestimation is relatively low. The low bayes factor even suggests that there is an overwhelming support for the null hypothesis. We discussed potential reasons why blur showed no significant impact on the results in Sections 3.5, 4.3 and 5.5. However, from the point of view of a practitioner in the

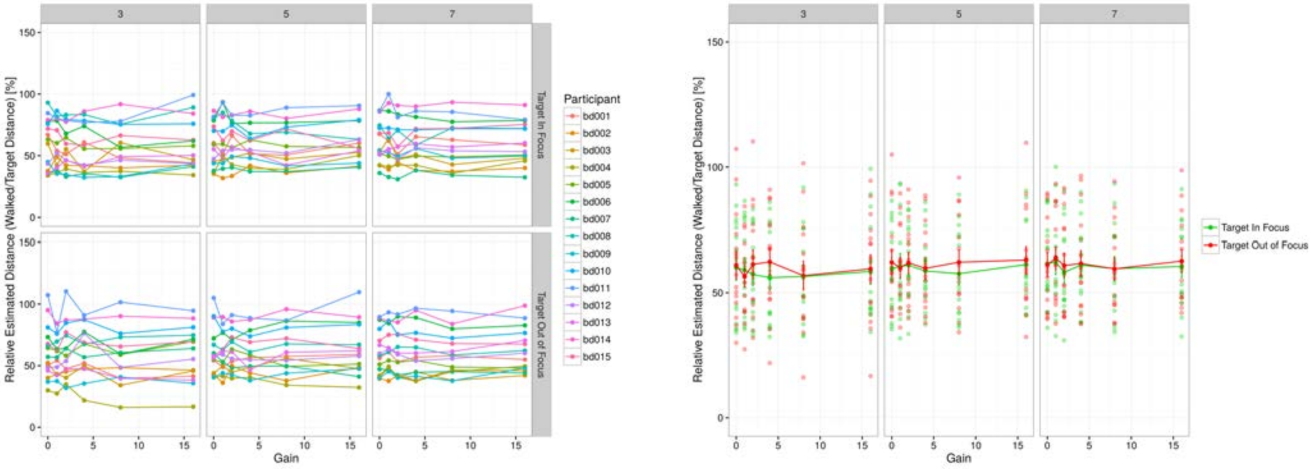

Figure 8: *Result plots of Experiment E3 depicting mean relative estimated distances in % at (left) participant level and (right) group level. Columns represent target distances in meters. Rows in (left) and colors in (right) represent if the target was in focus or out of focus. The blur strength is given with respect to the used gains. Points depict individual means of participants. Error bars show* ±1 *standard error.*

field of VR, we believe that it is warranted to provide the guideline that for practical purposes the effect of blur on distance and speed misperception in the visual imagery can be neglected.

This also can be applied to the current questions how much resolution of visual displays is required by indicating that unless the resolution is largely improved to approximate the visual acuity of the human eyes, blur due to lower resolutions is likely not an important cause of spatial misperception.

7 Conclusion

In this paper, we reported three psychophysical experiments that were conducted to investigate the influence of blur on distance and speed estimation. Because we found no significant effect and only very low effect sizes, we draw the conclusion that there is–if at all–only a negligibly small effect. Even if this result is, technically, a null result we believe that it is an important finding that will provide new insights to the research direction because there are important reasons why researchers might assume an influence of blur, which, so far, has not been proven or disproven in the published literature.

However, we have to consider that our findings are based on a snapshot of currently available HMD technology. Once available in the (distant) future, we will have to revisit effects of blur using an HMD with a field of view and resolution that match those of the human eyes. However, even then, blur might not prove to have much influence on distance and speed estimation due to the availability of stronger cues such as motion parallax and convergence.

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