Effects of Global Illumination of Virtual Objects in 360° Mixed Reality

Jingxin Zhang, Jannis Volz and Frank Steinicke
Human-Computer Interaction, University of Hamburg, Germany

Keywords: Global Illumination, 360° Mixed Reality, Spatial Localization, User Experience.

Abstract: Consistent rendering of virtual objects in 360° videos is challenging and crucial for spatial perception and the overall user experience in so-called 360° mixed reality (MR) environments. In particular, global illumination can provide important depth cues for localizing spatial objects in MR, and, moreover, improve the overall user experience. Previous works have introduced MR algorithms, which allow for the seamless composition of 3D virtual objects into a 360° video-based virtual environment (VE). For instance, for consistent global illumination, the light source in the 360° video can be detected and used to illuminate virtual objects and shadow calculation, or the 360° video can be reflected on specular virtual objects, known as environment mapping. Until now, it has not been evaluated if and to what extent global illumination of virtual objects in 360° MR environments improve spatial localization and user experience. To address this research question, we performed a user study in which we compared object localization with and without global illumination in 360° MR environments. The results show that the global illumination of virtual objects significantly reduces the localization error and improves the overall user experience in 360° MR environments.

1 INTRODUCTION

Head-mounted displays (HMDs) provide natural and immersive virtual reality (VR) experiences by supporting motion parallax, a wide field of view, and stereoscopic display (Steinicke, 2016). Although, HMDs are often used with computer-generated VR content, VR technology also allows viewing of immersive videos. Typically, such immersive videos are captured with 360° panoramic cameras, which support omnidirectional views of the surrounding environment. It gets possible, then, to visit a remote real-world scenario in an immersive way without the need to physically travel to the remote place. Traditionally, a remote scenario is displayed in the VR by attaching the input video onto a spherical surface as movie texture (Zhang et al., 2018), or as wrapped textures of a virtual skybox in the virtual environment (VE). Since the captured videos have been recorded from fix locations, 360° videos do not support motion parallax, and, moreover, stereoscopic cues are limited because the virtual scenes show VEs at larger distances. As a result, depth cues for spatial presence are limited in 360° VR (Bertel et al., 2019).

In mixed reality (MR) environments, these immersive videos can be augmented by virtual objects such as buildings, cars, or avatars (Milgram and Kishino, 1994) to blend real content (from the immersive video) with computer-generated virtual objects. The additional display of familiar objects inside immersive videos has also the potential to improve spatial perception (Müller et al., 2016). Such 360° video-based VEs and virtual objects are referred to as *360° MR environments* (Rhee et al., 2017). However, the combination of real contents and virtual objects in 360° video-based VEs, raises the challenge of consistent global illumination (Noh and Sunar, 2009; Pessoa et al., 2010). Global illumination allows for consistent lighting for virtual objects, reflections on specular surfaces, and shadows on the ground or other virtual objects (Steinicke et al., 2005). All of these effects provide users with important depth cues for visual perception and spatial localization (Zeil, 2000), and furthermore, improve the overall user experience (Steinicke et al., 2005).

Previous research (Rhee et al., 2017) has implemented seamless composition of 3D virtual objects into a 360° video-based VE by detecting the light source from the panoramic video and adjusting the virtual light source accordingly to create a consistent illumination of virtual objects. So far, it is not known if and to what extent this global illumination of virtual objects could improve spatial localization and user experience in 360° MR environments. To address this

Zhang, J., Volz, J. and Steinicke, F.
Effects of Global Illumination of Virtual Objects in 360° Mixed Reality.
DOI: 10.5220/0010861100003124
In *Proceedings of the 17th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (VISIGRAPP 2022) - Volume 2: HUCAPP*, pages 184-189
ISBN: 978-989-758-555-5; ISSN: 2184-4321

open research question, we first implemented a 360° MR environments with consistent global illumination. Second, we conducted a user study in which we compared the user's performance in an object localization task with and without global illumination in 360° MR environments, and furthermore, evaluated the effect of global illumination on user experience.

The remainder of this paper is structured as follows: Section 2 resumes related works. Section 3 introduces the design and procedure of the user study. Section 4 summarizes the results and Section 5 concludes the paper and discusses future work.

2 RELATED WORK

Spatial perception and localization in VEs are important research topics (Alatta and Freewan, 2017), and a vast body of literature has considered depth and size perception in virtual (Interrante et al., 2006; Bruder et al., 2012; Knapp and Loomis, 2004; Steinicke et al., 2009) and augmented reality (Hertel and Steinicke, 2021; Jones et al., 2011). The majority of the previous works has shown that distances to virtual objects are often underestimated, in particular, when the objects are displayed at larger distances (Plumert et al., 2005). It has also been shown that global illumination of virtual objects can improve the depth perception in computer-generated VEs as well as in AR scenarios, in which users see the real world through an optical see-through HMD such as Microsoft Hololens (Hertel and Steinicke, 2021).

Global illumination of virtual objects in 360° MR environments can provide important depth cues for visual perception and spatial localization, and add an additional level of realism to virtual objects (Haller et al., 2003), which could help to integrate virtual objects into the rendered VE based on 360° immersive videos smoothly and improve the overall user experience. For example, previous work by Steinicke et al. (Steinicke et al., 2005) introduced a MR setup in which a web camera was used to capture parts of the surrounding, which was in turn used to render lights, shadows, and reflections of specular virtual objects in a semi-immersive projection-based VR setup. Furthermore, Rhee et al. (Rhee et al., 2017) proposed an algorithm, which achieved seamless composition of 3D virtual objects into a 360° video-based VE by exploiting the input panoramic video as lighting source to illuminate virtual objects.

Though, there is a large body of literature regarding global illumination of virtual objects in typical VR and AR environments, and relevant algorithms to display virtual objects in 360° video-based VEs (Kruijff et al., 2010), the effect of global illumination of virtual objects on spatial localization and user experience in 360° MR environments still remain poorly understood.

3 USER STUDY

In the user study, we evaluated the effects of global illumination of virtual objects on spatial localization and user experience in 360° MR environments. The experiment received approval by our local ethics committee.

3.1 Hypothesis

We formulated the following hypotheses based on the previous findings for computer-generated VEs as described in Section 2:

- *H1: Participants will have higher localization accuracy with global illumination of virtual objects than without.*
- *H2: Participants will have better localization ability at closer distances compared to larger distances.*
- *H3: Participants will have better user experience with global illumination of virtual objects than without.*

3.2 Participants

15 voluntary participants (8 male, 7 female, average age 23.73 years, STD = 2.67) participated in the user study. All participants were students of computer science or human-computer interaction from our university. All participants had previous experience with VR and HMDs.

3.3 Experimental Setups

As illustrated in Figure 1, we generated a 360° video-based VE showing a wide grass field with a resolution of 8192x4096 pixels. The 360° video-based VE was rendered with the Unity Engine on a workstation, which has an Intel Core i7-4930K CPU with 3.40 GHz, an NVidia GeForce GTX 1080 Ti GPU and a 16GB main memory. The rendered scenario was displayed on a HTC Vive HMD with a resolution of 1080×1200 pixels per eye. The diagonal field of view is approximately 110° and the refresh rate is 90Hz. Participants used the HTC Vive controllers for interaction during the tasks. The global illumination of virtual objects in the 360° video-based VE

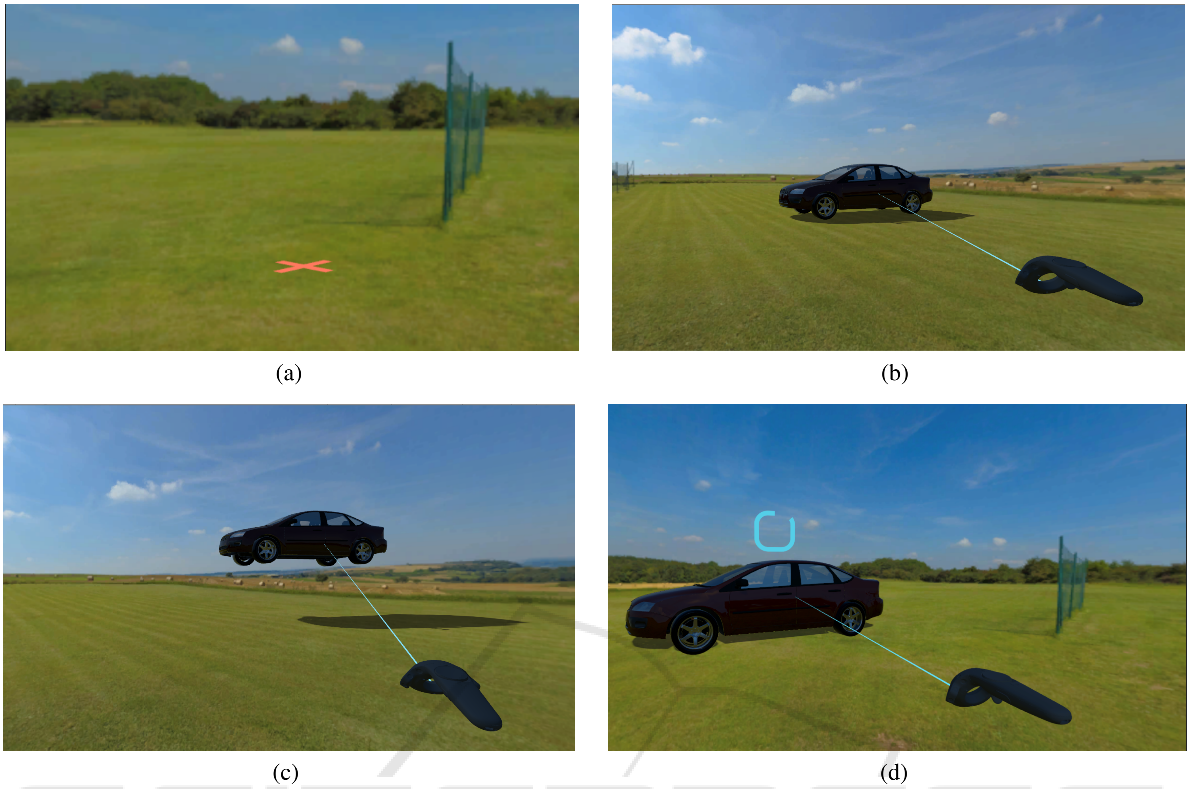


Figure 1: Screenshots of the task procedure with global illumination of virtual objects (images captured through HTC Vive Pro HMD): (a) the target position was marked with a red cross on the ground; (b) the virtual car was picked up from its default position using VR controllers; (c) the virtual car was being moved to the target position; (d) the placing operation was being confirmed.

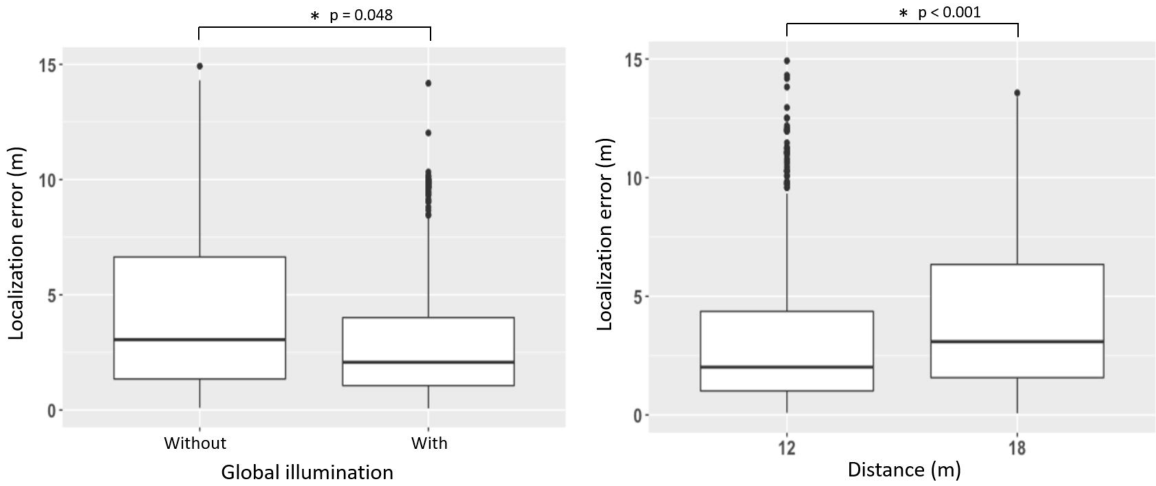
was implemented based on the algorithm proposed by Rhee et al. (Rhee et al., 2017; Rhee et al., 2018), which supported consistent lighting (extracted from the 360° videos), shadows (dropped on the manually defined grass ground), and virtual reflections (on the car's specular surface). The results are illustrated in Figure 1

3.4 Methods

During the user study, participants were required to stand in the center of the 360° video-based VE and move a virtual car from its default position (8m away from participants on the right side) to the target position (marked as a red cross on the ground) using VR controllers (see Figure 1). The task was designed with three factors in a 2 x 5 x 2 within-subject design: (i) *distance* (2 levels: 12m, 18m), (ii) *angle* (5 levels: 0°, 45°, 90°, 135° and 180° in yaw axis of the human body) and (iii) *global illumination effects* (2 levels: with and without).

Prior the user study, participants had to fill out a demographic questionnaire as well as Kennedy's simulator sickness questionnaire (SSQ) (Kennedy et al., 1993), and perform some training trials to get familiar with the operation and process. Afterwards, participants registered to the experimental system with their IDs and continued the formal process of the user study. Participants stood in the center of the 360° video-based VE and used VR controllers to move a virtual car from its default position to the target position as described above. The target position was determined by corresponding combinations of *distance* and *angle*, and marked on the ground with a red cross when every trial began until the moving operations of participants started. Participants were allowed to rotate their body during the user study (if required) to finish the localization task. The different stages of this task are presented in Figure 1.

As explained above, the user study was a within-subject design with 2 distances × 5 angles × 2 global illumination effects = 20 conditions, and each condition was repeated 6 times. Thus, every participant needed to finish 20 conditions × 6 repetitions = 120 trials during the task. All the trials were mixed and appeared in a randomized order to reduce the influence of participants' ability to memorize the target location on the localization results. For the entire user



(a) (b)

Figure 2: Results of the localization task: (a) global illumination effects on the localization error; (b) distance on the localization error.

study, 15 participants × 120 trials per participant = 1800 total trials were collected.

We measured the *localization error* in every trial after the participants confirmed their placing operations. The localization error indicates a bias between the target position and the actual location, where the participants placed the car, i.e., the geometric center point of the placed virtual car on the horizontal plane. In order to guarantee that for each tested target position, participants have a fixed duration to perceive and localize the virtual car, each trial was limited to 10 seconds.

Furthermore, after the user study, participants were asked to compare the global illumination effects (with vs without) and rate their *preference* with likable scales from 1 (not like it at all) to 7 (like it very much). Moreover, the post-SSQ questionnaire as well as the igroup presence questionnaire (IPQ) were also required (Schubert et al., 2001).

4 RESULTS

The experimental data was analyzed with the *analysis of variance* (ANOVA). Before the analysis, we performed a normality assumption check for all factor levels using the Shapiro-Wilk test (Royston, 1982), which did not show a strong indication of normal distribution in some cases. However, as shown in previous research (Glass et al., 1972; Harwell et al., 1992; Lix et al., 1996), moderate deviations from normality can be tolerated by the ANOVA analysis.

Figure 2a shows the effect of global illumination of virtual objects on the localization error. The average localization error is 4.296m (STD = 3.582) without global illumination, and 3.094m (STD = 3.05) with global illumination. This result indicates that the average localization error with global illumination of virtual objects was lower by 27.98% than without global illumination. The ANOVA results show a significant influence of *global illumination* of virtual objects on the localization error ($F_{1,14} = 4.688, p = 0.048, \eta^2 = 0.130$). These results show that the global illumination of virtual objects significantly help users to improve their localization accuracy in 360° MR environments, which confirmed hypothesis *H1*.

Figure 2 presents the effect of distance on the localization error. The average localization error is 3.179m (STD = 3.156) when the distance to the target position is 12m, and 4.21m (STD = 3.516) when the target distance is 18m. This result indicates that the average localization error at the distance of 12m is lower by 24.49% than at the distance of 18m. The

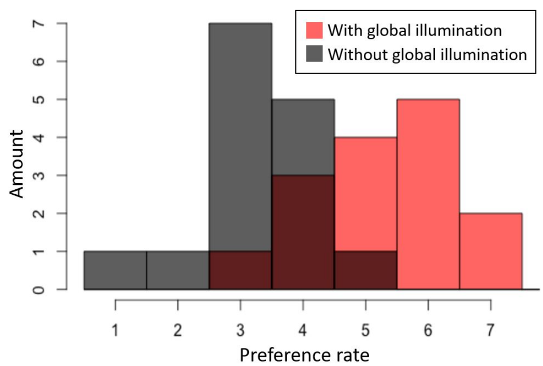


Figure 3: Results of preference rate on global illumination effects.

Table 1: Results of the IPQ.

	With global illumination		*Without global illumination*		*Significance*
	Score	*STD*	*Score*	*STD*	$p < .05$
Spatial presence	3.57	1.07	3.05	1.05	
Involvement	3.32	1.47	2.93	1.53	
Experienced realism	2.58	0.85	1.56	0.91	$*$

ANOVA result shows that the *distance* has a significant influence on the localization error ($F_{1,14} = 38.58, p < 0.001, \eta^2 = 0.099$). These results demonstrate that when localizing a virtual object in 360° MR environments, human users usually have better localization ability at closer distances. Thus, hypothesis *H2* was confirmed as well. However, no significant interaction effects between factors were found.

Figure 3 shows the preference rate of participants on the global illumination effects. For conditions with global illumination, the average preference rate is 5.27 out of 7, which is significantly higher than 3.27 for the situation without global illumination (confirmed by a one-sided Wilcoxon test with $p < 0.001$). This result show that participants have better user experiences when interacting with a 360° MR environment with global illumination of virtual objects than without. Thus, hypothesis *H3* can be confirmed.

Furthermore, participants' sense of presence in 360° MR environments was evaluated with the data from the IPQ. As presented in Table 1, for conditions with global illumination, the scores for spatial presence, involvement, and experienced realism are all higher than conditions without global illumination. Furthermore, we found a significant influence of global illumination on the *experienced realism* ($p = 0.002$), but no significant influence was verified for *spatial presence* and *involvement*. These results suggest that participants have better user experiences when interacting with a 360° MR environment with global illumination than without, especially in the aspect of experienced realism.

When participants were asked if they had any cognitive strategies during the task, 4 of them specifically reported that the global illumination and corresponding shadows of virtual objects were really helpful to estimate the placing location in 360° MR environments.

5 CONCLUSION

In this paper, we reported a user study in which we evaluated the effect of global illumination of virtual objects on the spatial localization and user experience in 360° MR environments. The results indicate that the global illumination of virtual objects could significantly reduce the localization error and improve the user experience, especially in the aspect of experienced realism. Participants also have better preference and evaluations on the experience with global illumination of virtual objects in 360° MR environments. These results highlight the importance of using global illumination in 360° MR environments, in particular, if correct spatial perception is important.

In future work, the extent to which each of the global illumination aspects (i.e., reflections, shadows, lighting) contribute to the overall spatial perception, sense of presence, and overall user experience will be evaluated in more detail. Furthermore, the effect of global illumination of virtual objects on other interactive operations (such as 3D object selection, 3D hand gesture interaction, etc.) in 360° MR environments will be also explored.

REFERENCES

Alatta, R. A. and Freewan, A. (2017). Investigating the effect of employing immersive virtual environment on enhancing spatial perception within design process. *ArchNet-IJAR: International Journal of Architectural Research*, 11(2):219.

Bertel, T., Campbell, N. D., and Richardt, C. (2019). Megaparallax: Casual 360° panoramas with motion parallax. *IEEE transactions on visualization and computer graphics*, 25(5):1828–1835.

Bruder, G., Pusch, A., and Steinicke, F. (2012). Analyzing effects of geometric rendering parameters on size and distance estimation in on-axis stereographics. In *Proceedings of the ACM Symposium on Applied Perception*, pages 111–118.

Glass, G. V., Peckham, P. D., and Sanders, J. R. (1972). Consequences of failure to meet assumptions underlying the fixed effects analyses of variance and covariance. *Review of educational research*, 42(3):237–288.

Haller, M., Drab, S., and Hartmann, W. (2003). A real-time shadow approach for an augmented reality application using shadow volumes. In *Proceedings of the ACM symposium on Virtual reality software and technology*, pages 56–65.

Harwell, M. R., Rubinstein, E. N., Hayes, W. S., and Olds, C. C. (1992). Summarizing monte carlo results in methodological research: The one-and twofactor fixed effects anova cases. *Journal of educational statistics*, 17(4):315–339.

Hertel, J. and Steinicke, F. (2021). Augmented reality for maritime navigation assistance-egocentric depth perception in large distance outdoor environments. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pages 122–130. IEEE.

Interrante, V., Ries, B., and Anderson, L. (2006). Distance perception in immersive virtual environments, revisited. In *IEEE virtual reality conference (VR 2006)*, pages 3–10. IEEE.

Jones, J. A., Swan, J. E., Singh, G., and Ellis, S. R. (2011). Peripheral visual information and its effect on distance judgments in virtual and augmented environments. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception in Graphics and Visualization*, pages 29–36.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., and Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, 3(3):203–220.

Knapp, J. M. and Loomis, J. M. (2004). Limited field of view of head-mounted displays is not the cause of distance underestimation in virtual environments. *Presence: Teleoperators & Virtual Environments*, 13(5):572–577.

Kruijff, E., Swan, J. E., and Feiner, S. (2010). Perceptual issues in augmented reality revisited. In *2010 IEEE International Symposium on Mixed and Augmented Reality*, pages 3–12. IEEE.

Lix, L. M., Keselman, J. C., and Keselman, H. J. (1996). Consequences of assumption violations revisited: A quantitative review of alternatives to the one-way analysis of variance f test. *Review of educational research*, 66(4):579–619.

Milgram, P. and Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems*, 77(12):1321–1329.

Müller, J., Rädle, R., and Reiterer, H. (2016). Virtual objects as spatial cues in collaborative mixed reality environments: How they shape communication behavior and user task load. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 1245–1249.

Noh, Z. and Sunar, M. S. (2009). A review of shadow techniques in augmented reality. In *2009 Second International Conference on Machine Vision*, pages 320–324. IEEE.

Pessoa, S., Moura, G., Lima, J., Teichrieb, V., and Kelner, J. (2010). Photorealistic rendering for augmented reality: A global illumination and brdf solution. In *2010 IEEE Virtual Reality Conference (VR)*, pages 3–10. IEEE.

Plumert, J. M., Kearney, J. K., Cremer, J. F., and Recker, K. (2005). Distance perception in real and virtual environments. *ACM Transactions on Applied Perception (TAP)*, 2(3):216–233.

Rhee, T., Chalmers, A., Hicks, M., Kumagai, K., Allen, B., Loh, I., Petikam, L., and Anjyo, K. (2018). Mr360 interactive: playing with digital creatures in 360° videos. In *SIGGRAPH Asia 2018 Virtual & Augmented Reality*, pages 1–2.

Rhee, T., Petikam, L., Allen, B., and Chalmers, A. (2017). Mr360: Mixed reality rendering for 360 panoramic videos. *IEEE transactions on visualization and computer graphics*, 23(4):1379–1388.

Royston, J. P. (1982). An extension of shapiro and wilk's w test for normality to large samples. *Journal of the Royal Statistical Society: Series C (Applied Statistics)*, 31(2):115–124.

Schubert, T., Friedmann, F., and Regenbrecht, H. (2001). The experience of presence: Factor analytic insights. *Presence: Teleoperators & Virtual Environments*, 10(3):266–281.

Steinicke, F. (2016). *Being really virtual*. Springer.

Steinicke, F., Bruder, G., Hinrichs, K., Lappe, M., Ries, B., and Interrante, V. (2009). Transitional environments enhance distance perception in immersive virtual reality systems. In *Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization*, pages 19–26.

Steinicke, F., Hinrichs, K., and Ropinski, T. (2005). Virtual reflections and virtual shadows in mixed reality environments. In *IFIP Conference on Human-Computer Interaction*, pages 1018–1021. Springer.

Zeil, J. (2000). Depth cues, behavioural context, and natural illumination: some potential limitations of video playback techniques. *Acta Ethologica*, 3(1):39–48.

Zhang, J., Langbehn, E., Krupke, D., Katzakis, N., and Steinicke, F. (2018). A 360 video-based robot platform for telepresent redirected walking. In *Proceedings of the 1st International Workshop on Virtual, Augmented, and Mixed Reality for Human-Robot Interactions (VAM-HRI)*, pages 58–62.