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Influence of Texture Fidelity on Spatial Perception in Virtual Reality

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Abstract: In this paper, we investigate the influence of texture fidelity on spatial perception in a standalone virtual reality application. To investigate this, we implemented a detailed virtual representation of an actual physical environment, namely a small one-bedroom apartment. The virtual apartment representation was tested in two different visual styles: high fidelity realistic textures, and a ”paper model” texture. Some test subjects experienced the virtual models using the actual physical apartment as transitional environment, other subjects experienced the model at an unrelated physical location. The environments were evaluated with 20 participants aged 20 to 61 and results indicated a systematic overestimation of distances in virtual reality for all conditions. The results showed that a higher texture fidelity had a positive influence on precision but no significant influence on accuracy. It was also showed that transitional environments negatively influenced precision, but had no significant influence on accuracy. Self assessments of presence from the experiment supported previous claims about a correlation between the level of detail in an environment and presence, but not a correlation between presence and distance perception.

1 INTRODUCTION

Architectural visualization, in its essence, is a process that transports a concept from a two dimensional perspective to a three dimensional image or a physical mockup. Due to the advancement of computers, there are also a plethora of software solutions that can facilitate creating a computer generated architectural model. Recently, the idea of combining Virtual Reality (VR) and game engines brings a new level of creativity and control to achieve high-realism scenes (Team, 2018).

Standalone VR headsets increases the potential of VR by affording greater flexibility than computer-tethered devices, and have more features than a browser or a mobile phone. In recent years, advancements in Head-mounted Display (HMD) technology has made the idea of owning a VR headset without the need of a VR Ready computer more palpable, as is indicated by the popularity of the Oculus Quest 2 (Lang, 2021).

While HMDs show promise, they still have some issues. One such issue is that spatial perception in VR has repeatedly been shown to be inaccurate, which brings into question the use of VR as a medium for architectural visualisation (Loyola, 2018).

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On the other hand, studies researching spatial perception in VR suggests that a high fidelity, low latency, immersive environment can decrease the inaccuracies in user's distance perception (Interrante et al., 2006) (Phillips et al., 2009a) (Phillips et al., 2009b).

With this in mind, the aim of this study was to "*investigate the influence of texture fidelity on spatial perception in standalone virtual reality for architectural visualization.*"

2 SPATIAL PERCEPTION IN VIRTUAL REALITY

Spatial perception in Virtual Reality (VR) has been extensively studied and the consensus appears to be that spatial perception in VR is compressed compared to spatial perception in the real world (Interrante et al., 2006) (Loyola, 2018). I.e., in VR people generally feel that the space is smaller than its real physical counterpart. If such spatial mis-perception is indeed the case, the concept of using VR as a tool in architectural design and validation processes is obviously compromised, as it can lead to misrepresentation by architects and clients alike (Loyola, 2018).

A series of studies by Interrante et al. investigates

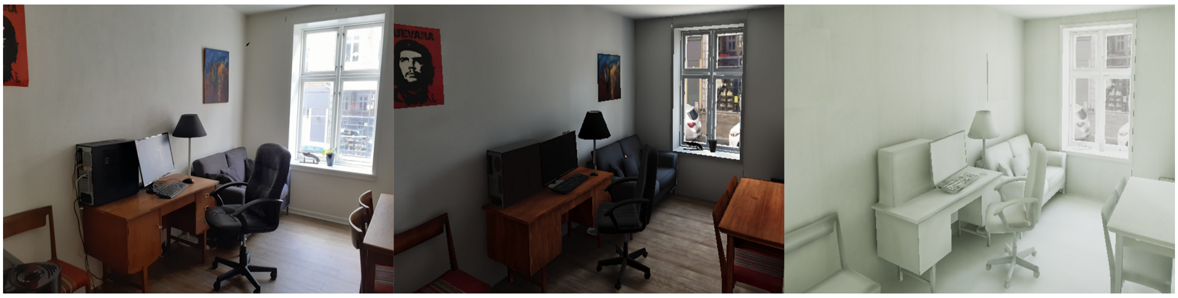

Figure 1: Spatial perception was assessed with verbal assessment in virtual environments with different texture fidelities modelled after a real life room (left image).

the influence of immersion and fidelity on spatial perception in VEs (Interrante et al., 2006) (Phillips et al., 2009a). Their main findings were that distance perception appears to not be significantly compressed in high fidelity, low latency, immersive environments and even less if the VE represents an exact replica of the room in which the user is located in, in the real world (Interrante et al., 2006) (Phillips et al., 2009a). In their initial paper on the subject, they also suggest that the user's sense of presence might have an influence on their estimates (Interrante et al., 2006).

In a more recent study by Interrante et al. they investigated distance estimation in a non-photorealistic VE against a photorealistic VE (Phillips et al., 2009b). The findings of their study supports their previous findings as the participants were significantly better at assessing distances in the photorealistic environment than in the non-photorealistic environment.

In their paper it is also discussed that a possible explanation for their findings could be that the unrealistic nature of their representation of a non-photorealistic environment possibly interfered with the participants' presence in the environment, as it deviates a lot from the real world (Phillips et al., 2009b).

Hornsey and Hibbard further support the finding that distance estimation is biased towards underestimation, (Hornsey and Hibbard, 2021). They also found that the more pictorial cues are added to a scene, the better the distance estimation will be (Hornsey and Hibbard, 2021). Finally, they found that texture gradients have a positive influence on distance estimation, especially at very short distances (Hornsey and Hibbard, 2021).

Based on the above, we found it interesting to investigate whether the texture fidelity alone has an influence on distance assessment even if applied to the same geometry. In order to measure the participants perceived distances a few methods for this were reviewed.

2.1 Measurement Methods for Perceived Distance

To evaluate the users' spatial perception of our VE, a measurement method was needed. Choosing a measurement method for perceived distance can be difficult as perception is very abstract. Table 1 shows the prominence of various different approaches in previous studies on spatial perception in VR.

Table 1: Measurement methods for perceived distance from previous studies including whether they can measure ego-centric or exo-centric distances.

Method	Ego or Exo	References
Verbal Assessment	Both	(Loyola, 2018) (Peer and Ponto, 2017) (Ng et al., 2016) (Armbrüster et al., 2008) (Gagnon et al., 2020) (Klein et al., 2009) (Kelly et al., 2017)
Blind Walking	Ego	(Interrante et al., 2006) (Peer and Ponto, 2017) (Kelly et al., 2018) (Li et al., 2015) (Kelly et al., 2017) (Klein et al., 2009) (Phillips et al., 2009b)
Resizing Objects	Both	(Kelly et al., 2018) (Kelly et al., 2017) (Jensen et al., 2020)
Time Imagined Walking	Ego	(Peer and Ponto, 2017) (Klein et al., 2009)
Resizing Environment	Both	(Jensen et al., 2020)
Blind Throwing	Ego	(Peer and Ponto, 2017)

Having explored the methods shown in Table 1, we chose to use verbal assessment as our measure method. Even though some studies have suggested that blind walking is more reliable (Ng et al., 2016), evidence found by Klein et. al suggests that this is only the case in larger outdoor areas and that the methods have similar reliability in indoor scenarios such as ours(Klein et al., 2009).

3 IMPLEMENTATION OF THE VIRTUAL ENVIRONMENT

In a mobile Virtual Reality (VR) context, Unity's built-in Universal Rendering Pipeline (URP) appears to be the optimal render pipeline. Since the Oculus Quest platform can be considered a mobile platform, the ease-of-use and mobile centered optimizations of URP make it a solid foundation to achieve the level of quality desired, considering the computational limitations of the platform.

3.1 Virtual Reality Implementation

VR Implementation for the application was done using Unity's *XR Interaction Toolkit*, which affords adding an XR Rig to the environment. The XR Rig is automatically connected to the Head-Mounted Display (HMD) being used by a user and the camera follows the HMD position, while controller objects follow the controllers being used. The Field-of-View (FOV) set for the rendered camera is 98 degrees Vertical, and 128 degrees Horizontal.

3.2 Modelling the Virtual Environment

Recreating a real indoor environment in VR required us to create 3D models of the environment and furniture. The foundation of the environment for our experiment was created with a method similar to what was previously explored by Ozacar et al. (Ozacar et al., 2017), starting with a floor plan made in Sweet Home 3D, which was exported to Unity as a 3D model with walls, floors and ceilings.

3D models representing furniture recreated from the real world were placed in the environment in accordance with scale and distance translated from the metric system to Unity's measuring system. These models were created in either Blender or Maya and textured with Substance Painter. For details like text, logos or stickers some manipulation of the textures were done in Adobe Photoshop. The models were created with a relatively low amount of polygons to limit the memory usage of the application as we are working with standalone headsets, as was also highlighted by Unity as an important factor in optimizing performance of applications (Technologies, 2020). To accurately represent the chosen apartment, pictures of the furniture were taken and used as reference, as shown in Figure 2.

Figure 2: A sample of the modelled furniture, with the left image being the real life version, in the respective order a cupboard, a desk, an office chair and a mirror.

3.3 Virtual Environment Illumination

Lighting in the environment was achieved by combining a mixed directional light source (baked indirect lighting and real-time shadows), a baked area light source, and global illumination (GI). The directional light was chosen to simulate direct sunlight with a downwards facing angle entering through the window, and the area light was used to simulate the effect of light from the sky. The sky area light was placed just outside the window, facing into the room. In combination these two types of light sources constitute a typical, and efficient, approach to emulating exterior daylight affecting an indoor scenario, (Birn, 2014).

The reflectivity of a material in a virtual world has a significant effect on the aesthetics of the object that it is applied to (Manson and Sloan, 2016). To increase the materials ability to react to light in a realistic way, Physically Based Rendering (PBR) was utilized. To simplify the computation of reflections in the environment, a reflection probe was used.

The reflection probe had a resolution of 256 pixels, and was used to ensure that light reflections (with colours corresponding to objects they bounce off) were present in the environment (see Figure 3).

Additionally, shadows were computed as shadow maps, and *ambient occlusion* was applied to all objects. Finally a *global volume* for post processing effects was applied to the environment, allowing the incorporation of *white balancing*, *gamma and gain altering* and *tone mapping*. The parameters for these were set as shown in Table 2.

Table 2: Parameters used for Global Volume Post Processing Effects

Effect	Parameter
Tonemapping	ACES
Gamma	1.32
Gain	1.29

Figure 3: A reflection probe from the environment. Top part is the probe itself, with the bottom part being the cubemap.

4 EXPERIMENTAL DESIGN

The independent variable in the experiment was the texture fidelity of the environment with the two conditions being: convincing textures and paper textures. We used a between group design with two groups of participants, each assigned to one of the conditions. These conditions can be seen in Figure 4.

In the experiment we measured the participants' spatial perception of the room, by asking them about certain distances and getting them to verbally assess them. The measurement method was chosen based on the small size of the room as described in Section 2.1, while other viable methods were presented in Table 1.

Figure 4: Side-by-side comparison of the two conditions, with the left side being convincing textures and the right side being the paper textures.

The primary interest of the study was to investigate if convincing textures have an influence on the user's spatial perception of a Virtual Environment (VE). To investigate the influence we came up with the following set, **"A"**, of hypotheses.

Hypothesis A1: *Participants experiencing the scenario with convincing textures should assess distance with higher accuracy and precision than the ones experiencing the paper textures.*

Hypothesis A2: *Participants experiencing the scenario with convincing textures should assess distance with lower accuracy and precision than the ones experiencing the paper textures.*

Null Hypothesis A0: *There is no significant difference in the accuracy or precision of assessing distance, between participants experiencing convincing textures and paper textures.*

Previous research done by (Steinicke et al., 2009) (Interrante et al., 2006) (Phillips et al., 2009a), have explored the effects of "transitional environments". This phenomenon implies that depth perception is positively affected by entering a VE from the physical environment it represents. Thus, in the design of our experiment, half of the participants entered the VE from the modelled apartment, with the other half entering the VE from an unrelated location. The subset, **"B"**, of hypotheses is as follows:

Hypothesis B1: *Participants entering the VR scenario from the real-life equivalent of the virtual environment should assess distance with higher accuracy and precision than the ones who enter from a unrelated location.*

Hypothesis B2: *Participants entering the VR scenario from the real-life equivalent of the virtual environment should assess distance with lower accuracy and precision than the ones who enter from an unrelated location.*

Null Hypothesis B0: *There is no significant difference in the accuracy or precision of assessing distance, between participants entering from the real-life equivalent of the virtual room and an unrelated location.*

4.1 Participants

Participants for the experiment were contacted and recruited through social media or email. For each of the sub-experiments 10 participants were recruited - giving the experiment a total of 20 participants. The age of the participants ranged from 20 to 61 - all with normal (20/20) or corrected vision.

4.2 Apparatus

As we focused on standalone VR - the Oculus Quest 2 Head-Mounted Display (HMD) was used in the experiment, as it has a higher resolution than the original Quest (Technologies, 2021).

The inter-pupilary distance (IPD) of the Quest 2 can be physically set as 58, 63 or 68mm, which was set to fit each individual participant, as a wrong IPD can result in the view being blurry (Corporation, 2020). The Quest 2 further supports a 89 degree horizontal Field-of-View (FOV), 90 degree vertical FOV and 127 degree diagonal FOV (Brown, 2021).

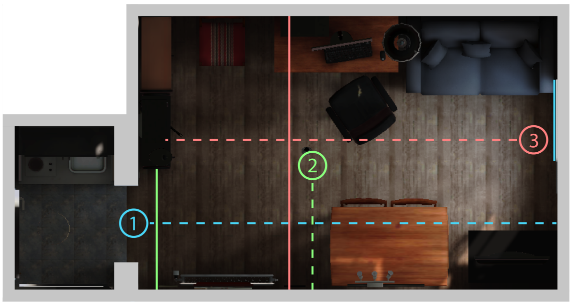

Figure 5: The teleportation spots are shown with a circle, color-coded to match the distances assessed from them. The ego-centric distances are shown with dotted lines, while the exo-centric distances are shown with full lines.

4.3 Procedure

Firstly, the facilitators informed the participants about the course of the experiment and ensured that they were familiar with the HMD and the buttons they would have to use on the controllers during the experiment. In this introduction the physical IPD on the HMD was also set to the best fitting state for the participants. Once the participants were ready they would enter the environment matching the respective condition they were assigned to.

The participants would be asked to walk around and explore the room for 1 minute, as it has been proven to improve spatial perception in VEs (Kelly et al., 2018), before beginning the distance assessment tasks.

After exploring the room, the participants would be asked to press the trigger to teleport to the first spot in the room, which they had to assess distance from. After teleporting, they were told to hold the Oculus button until their position and orientation was reset. This ensured that all participants were assessing distances from the same location in the VE. After assessing two distances in a spot, they would be asked to teleport to the next spot following the same procedure.

The spots and the distances are illustrated in a top-down view of the environment in Figure 5. In total the participants had to assess six distances ranging from 105cm to 440cm within the VE. While each participant was assessing distances, the facilitator would log the assessments manually.

After finishing the assessments in Virtual Reality (VR), the participants' sense of presence in the environment was measured with the Igroup Presence Questionnaire (IPQ) (igroup.org, 2016).

The questionnaire was included in the experiment to see if the conditions had any influence on presence, as it was suggested by Interente et al. that the fidelity of the environment, presence and depth perception is correlated (Interrante et al., 2006) (Phillips et al., 2009a).

Following the questionnaire, a follow-up unstructured feedback session was initiated using the following inquiry:

> *Did you think any of the objects looked less or more believable than others?*

The purpose was to elicit the participants' thoughts on the environment and the perceived distances.

5 RESULTS

The presentation of the results from the experiment, described above in Section 4, is split into three categories: Distance Assessment, Presence and Feedback on the Environment. To validate that the results of the experiment were minimally influenced by the performance of the application on the Head-Mounted Display (HMD), the framerate was logged. This showed that the condition with convincing textures had a median framerate of 48fps, which is marginally less than the paper condition which had a median framerate of 52fps.

5.1 Distance Assessments

In order to visualize and analyze the distance assessments from the experiment, the amount of error in the participants' assessments for all distances were expressed in percentage making them comparable - similarly to what was done in prior research by Loyola et. al (Loyola, 2018). For our analysis of significant difference between the groups, we chose to analyze the absolute values to focus purely on their difference in accuracy. Accuracy being defined as: *"how much the assessments deviate from the actual distances"*. In the plots, however, we will use the relative errors to show the precision of the assessments. Precision is here defined as: *"how similarly participants within a certain group assessed the distances"*.

5.1.1 Distance Assessment Compared Between the Conditions

The experiment showed no significant difference (p-value $= 0.83 > 0.05$) in the absolute error deviations from the participants' distance assessment between the two conditions, convincing textures and paper textures. There is therefore no evidence that the conditions influenced accuracy in distance assessment.

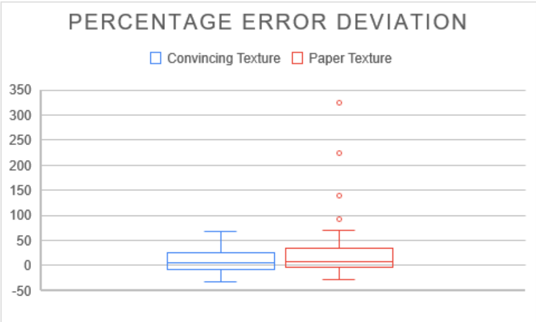

Figure 6: Visualization of the precision within each condition showed with relative error deviation in percentage.

The standard deviation of the relative error in percentage for the condition with convincing textures was 23.17 percent, whereas standard deviation for condition with paper textures was 58.98 percent. As the standard deviation was lower for the condition with convincing textures, compared to the condition with paper textures, it shows that the condition with convincing textures has increased precision of assessment within the sample.

The plot in Figure 6 shows a comparison of the relative error deviation in percentage between the conditions.

5.1.2 Distance Assessment Compared Between Apartment and Unrelated Location

The experiment also did not show significant difference (p-value $= 0.25 > 0.05$) in the absolute error deviations from the participants' distance assessment between the locations. In our experiment there is therefore also no evidence that being in the real life equivalent of the Virtual Environment (VE) during the experience has an influence on the accuracy of distance assessments.

The standard deviation of the relative error in percentage for the participants who experienced the experiment in the real life equivalent of the VE was 55.32 percent, whereas the standard deviation for the ones who tried it in the unrelated location was 31.18 percent. As the standard deviation was lower for the ones experiencing the experiment in the unrelated location, compared to the ones experiencing it in the real life equivalent of the VE, it shows that experiencing it from the unrelated location has increased precision of assessment within the sample.

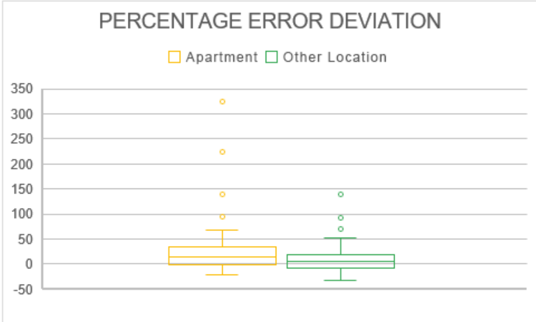

Figure 7: Visualization of the precision within each location showed with relative error deviation in percentage.

The plot in Figure 7 shows a comparison of the relative error deviation in percentage between the conditions.

5.2 Presence

The results from the presence questionnaires were averaged and made into visual representations as presence profiles. No significant difference in presence was found between the participants who tried the experience in the real life equivalent of the VE (i.e apartment) or in the unrelated location.

The means of the sub-scales of presence between the conditions (i.e. convincing textures and paper textures) as shown in the presence profile in Figure 8.

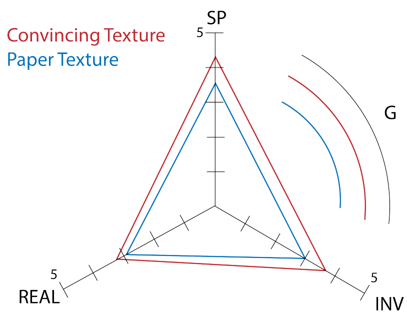

Figure 8: The presence profile showing how the means of each condition between the conditions are distributed for each presence sub-scale.

The self-assessments of presence showed statistically significantly higher scores in the sub-scales

Spatial Presence (SP) and Involvement (INV) within the convincing textures condition compared to the paper textures. Although for the general "sense of being there" (G) and sub-scale Experienced Realism (REAL) there was no significant difference between the conditions.

5.3 Feedback on the Environments Visuals

Seven of the participants stated that the outside of the window looked slightly more "blurry" than the rest. One participant described it as being immersion breaking as it was flat compared to the rest of the environment and two others stated that the window frame was jagged as well.

The mirror was also mentioned by multiple people. Four participants stated that it was in accordance with real life and one participant even stated that it gave a him a better affordance of depth view. Although, three participants stated that the mirror was a bit jagged compared to the environment, while two participants noted that it was weird to not see themselves in the mirror, and a single person stated that he did not even recognise it as a mirror at first.

Another interesting finding was that five of the participants, who tried the experience from within the real life equivalent of the VE, stated that the room seemed smaller within the VE compared to real life. This is particular interesting as most participant overestimated the distances. One participant also stated that the VE was not as lit as the real life counterpart.

6 DISCUSSION

Our findings suggest, that the condition with convincing textures results in a higher precision than the paper texture condition, however, no significant difference was observed in terms of accuracy between these conditions. This contradicts research by Interrante et al. (Interrante et al., 2006) (Phillips et al., 2009a) (Phillips et al., 2009b). A difference between the texture conditions that might have had an influence on this is the illuminance levels. In the version with paper textures, the white material being reflected by the reflection probe illuminated the room more than the colours from the convincing textures did. So even though the lighting setup and parameters were the same, the environment with the paper textures was more illuminated. This can be seen in Figure 4.

Furthermore, the precision between locations was found to be higher when experiencing the Virtual Environment (VE) from the unrelated location than the apartment, with accuracy being unaffected. This is in contrast to previous research done by Steinicke et al. (Steinicke et al., 2009).

Another interesting finding was that participants in general seemed to overestimate the distances, which contradicts previous research that has shown tendencies of general underestimations in Virtual Reality (VR), as presented in Section 2. It is also interesting to note that five of the participants entering the experience from the real life equivalent of the VE, stated that the room seemed smaller in the VE, but still overestimated the distances in their assessments.

In terms of the users' sense of presence, the convincing textures scored significantly higher in spatial presence and involvement. This correlates to prior research which suggests that a higher visual fidelity of an environment positively influences presence (see Section 2). However, the correlation does not, as previous research have suggested, significantly correlate with the distance assessments as described above. There was no significant change in any of the presence sub scales between the entering locations, which contradicts previous research into the effect of transitional environments on presence.

A possible threat to both validity and reliability, as has been eluded to earlier in Section 2.1, is the measurement method of verbal assessment in metrics, which in a few earlier studies been suggested to be unreliable. It is likely that some of our outliers in the experiment is due to the verbal assessment method being unreliable for some individuals, since verbal assessments in metric is not something that is commonly used in everyday life for most people. A few participants also stated that they for some of their distance assessments, such as with the window frame, used knowledge of familiar sizes of window frames, instead of naïvely evaluating the distance in the VE. Another threat to the reliability of the test is that the experiment only had 20 participants. This makes it impossible to properly generalize our findings.

However, since the majority of our findings contradict previous research, we explored some of the differences in methods between previous studies and ours, and concluded that the main difference was that we used a relatively small room compared to research in this field. We hypothesize that these size differences in the VEs may have been the main cause behind the contradictions. We suggest an investigation of this through a large-scale validation study with a number of VEs of various sizes rather than just one, and a larger sample of participants. This could be done using the method we applied in this study, or, more interestingly, a variety of the methods presented in Table 1.

7 CONCLUSION

The aim of the study was to investigate the influence of texture fidelity on spatial perception of a Virtual Environment (VE). An experiment was conducted with participants assessing distance in two different VEs: one environment having convincing textures and one having paper textures, both with the same geometry. The experiment was split into two sub experiments investigating whether the location from where you enter the VE has an influence on the assessments, with one of the locations being the real life equivalent of the VE.

The findings suggested that the environment with convincing textures had higher precision than the one with paper textures. However, there was no significant difference between the accuracy of assessments in neither the texture fidelities nor the entering locations. The entering locations also did not have any influence in accuracy, while the precision of assessments were higher for participants entering from an unrelated location than the real life equivalent of the VE. Both of these findings contradict previous research into transitional environments.

A more interesting finding was the consistent overestimations in distance assessments which contradicts previous studies, which we hypothesize could be caused by the evaluated VE being smaller in size than those used in previous research. We suggest that this is researched further by evaluating distance perception in VEs of various sizes, using either the method used in this paper, or a variety of those presented in Table 1.

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