The Influence of a Low-Resolution Peripheral Display Extension on the Perceived Plausibility and Presence

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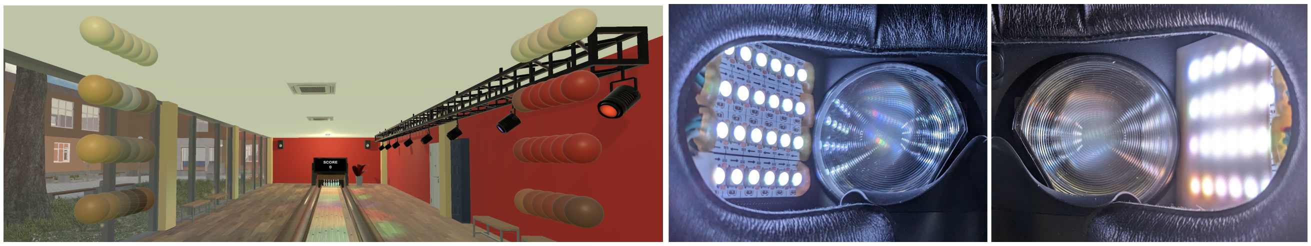


(a) VR environment with light probes which determine the LED colors.

(b) Peripheral Display Extension with 4 x 6 LEDs on each side integrated into the HTC Vive Pro.

Figure 1: The VR bowling application and peripheral display extension used for the experiments.

ABSTRACT

The Field of View (FoV) is a central technical display characteristic of Head-Mounted Displays (HMDs), which has been shown to have a notable impact on important aspects of the user experience. For example, an increased FoV has been shown to foster a sense of presence and improve peripheral information processing, but it also increases the risk of VR sickness. This article investigates the impact of a wider but inhomogeneous FoV on the perceived plausibility, measuring its effects on presence, spatial presence, and VR sickness as a comparison to and replication of effects from prior work. We developed a low-resolution peripheral display extension to pragmatically increase the FoV, taking into account the lower peripheral acuity of the human eye. While this design results in inhomogeneous resolutions of HMDs at the display edges, it also is a low complexity and low-cost extension. However, its effects on important VR qualities have to be identified. We conducted two experiments with 30 and 27 participants, respectively. In a randomized 2x3 within-subject design, participants played three rounds of bowling in VR, both with and without the display extension. Two rounds contained incongruencies to induce breaks in plausibility. In experiment 2, we enhanced one incongruency to make it more noticeable and improved the shortcomings of the display extension that had previously been identified. However, neither study measured the low-resolution FoV extension's effect in terms of perceived plausibility, presence, spatial presence, or VR sickness. We found that one of the incongruencies could cause a break in plausibility without the extension, confirming the results of a previous study.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **HCI theory, concepts and models**; **Empirical studies in HCI**; *Interaction devices.*

KEYWORDS

VR, experience, plausibility, congruence, presence, spatial presence, immersion, field of view

ACM Reference Format:
Larissa Brübach, Marius Röhm, Franziska Westermeier, Carolin Wienrich, and Marc Erich Latoschik. 2024. The Influence of a Low-Resolution Peripheral Display Extension on the Perceived Plausibility and Presence. In *30th ACM Symposium on Virtual Reality Software and Technology (VRST '24), October 9–11, 2024, Trier, Germany*. ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3641825.3687713

VRST '24, October 9–11, 2024, Trier, Germany

ACM ISBN 979-8-4007-0535-9/24/10
https://doi.org/10.1145/3641825.3687713

1 INTRODUCTION

The field of view (FoV) of head-mounted displays (HMDs) increases with almost every generation. While the Oculus Rift Development Kit, released in 2013, had a FoV of 90° [5], the Vive Pro Eye today has a FoV of 98° [6]. Some headsets, like the Pimax Crystal QLED, even have a FoV of 125° [7]. However, the human eye has a FoV of roughly 214°, almost double the widest FoV currently available in HMDs. However, these extensions have their price, both financially and in terms of weight and the required computing power. The Pimax Crystal QLED, for example, is almost twice as expensive as the Vive Pro Eye and weighs about 300g more [6, 7]. Another issue with HMDs with wider FoVs is that they can cause negative effects on the user. Studies have shown that a wider FoV can increase motion sickness [18, 19]. To counteract this, the FoV is often even artificially reduced [1, 10]. A larger FoV can also decrease the user's posture stability [9]. On the positive side, a wider FoV can offer benefits for one's XR experience. It can increase the feeling of presence [8], enjoyment[19], and spatial awareness [22]. It can also aid people in wayfinding tasks in extended reality (XR) [19, 24]. The comparison between a wider-than-normal FoV (>90°) in comparison to a "normal" FoV is underrepresented in virtual reality (VR). Most studies either artificially decrease the FoV or don't use a head-mounted display (HMD) but rather projection screens. The studies mostly focused on high-resolution displays, which, as mentioned above, come with the trade-off price and weight.

One solution to counteract the weight and price problem of larger FoV HMDs could be to integrate a low-resolution peripheral display extension. Jones et al. [15] proposed the use of a simple LED bar within an HMD. They conducted a series of studies examining the effect of static peripheral stimulation on distance perception and spatial scale with an HMD. They found that a constant white light could increase participants' distance and size estimation. Xiao and Benko [33] proposed a more elaborate system in 2016. They integrated a sparse peripheral display extension into an existing headset to create a larger FoV. Similarly, Gruenefeld et al. [11] used a radial peripheral display extension to help with a navigation task. However, the influence of these display extensions and their a priori incongruencies (i.e., resolution, frame rate, latency differences) have not been specifically researched with regard to important XR qualia, like presence, spatial presence, or plausibility.

Recent discussions have shifted their attention from presence to plausibility. A model proposed by Latoschik and Wienrich [17], called the Congruence and Plausibility Model (CaP model), puts plausibility in the center of attention. The plausibility of an application in this model is influenced by the three-layer manipulation space, consisting of the sensation, perception, and cognition layer. The resulting plausibility then, in turn, influences other qualia, such as presence, spatial presence, or body ownership. Previous work has looked at different incongruencies that influence plausibility and its effects on other qualia. Another way to study plausibility could be to influence it through a higher immersion on the perception layer. This could be achieved by a wider FoV.

Our study aims to look at a wider FoV's effects on the user's perceived plausibility in VR. However, we do not use a higher-resolution display for the extension. The wider FoV is achieved by implementing a low-resolution peripheral display extension. This allows an increase of the FoV from 90° to 120°. Additionally, incongruencies were introduced to see whether the wider FoV would have an effect on the perception of them. We conducted two experiments, a pre- and a main study (in the following called experiment 1 and 2), to research the effects of the wider FoV and the incongruencies on the perceived plausibility, presence, and spatial presence, as well as VR sickness. The results suggest that a wider FoV through a low-resolution extension does not influence the perceived plausibility or the feeling of presence and spatial presence. It also did not increase the VR sickness as a high-resolution solution would.

2 RELATED WORK

2.1 Influence of FoV on XR Qualia

The effects of different FoVs on XR qualia, like presence, spatial presence, simulator sickness, enjoyment, and learning success, have been researched in many studies in the past. Technical immersion can be defined as the objective system characteristics of a VR system [28]. The FoV is an objective technical element of a VR system, so it can influence immersion.

A meta-review from 2016 by Cummings and Bailenson [8] found 83 studies examining immersion's effects on presence. In general, technical immersion had a medium-sized effect on presence. Presence is defined as the realistic response from users to a virtual environment [27]. However, they found that a wider FoV has a significantly greater effect than, for example, visual and auditory content quality. Both (FoV and visual/auditory quality) are determinants for immersion. Seay et al. [24] used a driving simulation with the NAVE (non-expensive automatic virtual environment) system consisting of three large screens. Among other things, they compared two different FoVs (60° vs. 180°). Participants were tasked with finding a specific waypoint and then finding their way back without backtracking. Their results show that participants reported higher presence scores in the wide FoV condition. Lin et al. [19] compared four different FoVs (60°, 100°, 140°, and 180°) to investigate their influence on presence, enjoyment, and simulator sickness. They also used a driving simulator and tasked participants with driving through a virtual environment. They could show that presence and simulator sickness increased with a wider FoV. The enjoyment decreased with a wider FoV, which might be a result of the higher simulator sickness.

However, an increased FoV can also have unexpected effects on the user. Duh et al. [9] looked at the effects of an increased FoV on the balance of participants in an immersive environment. Participants were tasked to keep their balance while watching a moving scene. They stood on a balance system that collected data about their posture. Their results show that an increased FoV led to greater instability in the posture of the participants.

In 2016, Xiao and Benko [33] developed a sparse peripheral display extension to augment a wider FoV in VR and AR. They placed LEDs in different HMDs, which then lit up in the corresponding colors of the environment outside the normal viewing range of the HMDs. They served as a low-resolution, low-cost display extension, which extended the FoV up to 190° horizontally. The sparse peripheral display was used in both virtual and augmented reality headsets. They were tested in two different user studies. One was to investigate the benefits of the extension during task performance, where participants had to find a target in the environment. The other one was to study the effect on simulator sickness, where participants had to follow a square around with their heads and move around a virtual environment. The results show that the displays can improve situational awareness and help show peripheral information and were generally preferred by the participants. It was also shown that the sparse peripheral display can help reduce motion sickness. The authors report that a negative effect of their implementation is an impact on the application's performance. While these findings sound very promising, the authors did not look at common factors influencing one's XR experience, like presence, spatial presence, or plausibility.

Lubos et al. [20] placed a single array of LEDs around the lenses of an Oculus Rift DK2. They were interested if the peripheral display extension had an influence on the participants' feeling of presence and their behavior while navigating through a virtual environment. They found that participants enjoyed using the display extension and that they explored the virtual environment more. They did not find a difference in cyber sickness when using the display extension compared to no display extension. However, they did not find a significant difference in the presence scores. Similarly, Gruenefeld et al. [12] developed a low-cost prototyping tool for the development of peripheral display extension in HMDs. They later used this to research the influence of a peripheral display extension on a navigation task in VR [11]. They placed 18 LEDs around each of the HMD's lenses to aid with a navigation task. These LEDs should cue the direction of objects that were out of the participant's FoV. They evaluated the system with a 360° video and found that the LEDs were suitable for direction cueing.

Nakao et al. [21] implemented an 8x8 LED matrix into smart glasses. These enabled users to recognize patterns in their peripheral vision. However, their prototype is limited in the kind of information it can display, and it is not directly connected to a virtual environment. In a small user study, they showed that participants were able to recognize information from the display, especially horizontal movements. However, they did not evaluate their prototype regarding other XR qualia, like presence or plausibility. Yamada and Manabe [34] developed a different type of peripheral extension. They used Fresnel lenses to expand the FoV by filling the peripheral view around the HMD lens with a blurred image. Unfortunately, the authors did not validate their approach with a user study.

2.2 Plausibility in XR

There have been various studies on the role of plausibility in the past [25, 26, 29]. The issue around the importance of plausibility in XR has recently gained attention with the proposal of the congruence and plausibility model (CaP model, figure 2) by Latoschik and Wienrich [17]. Here, in contrast to Slater [27], plausibility is seen as a holistic construct rather than just a cognitive one and as the main influencing factor on one's XR experience. It is also not seen as an illusion. Plausibility can be seen as a match between the user's expectations, previous knowledge, and the XR environment and scenario. Qualia like placeness (in replacement for the place illusion), embodiment, presence, and others are seen to be influenced by plausibility. The plausibility, in turn, results from a weighted function of different (in)congruencies on the three-layer manipulation space. These three layers are the cognitive (top-down), perceptual (bottom-up), and sensation (bottom-up) layer. Congruence can be manipulated on all three of these layers.

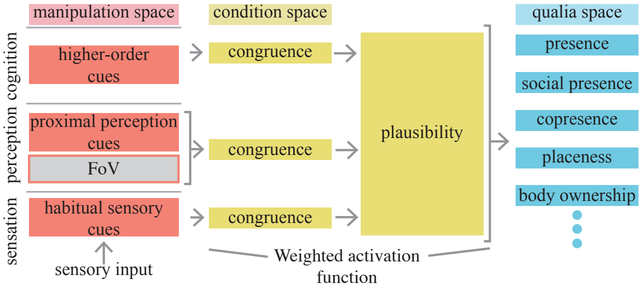


Figure 2: Congruence and Plausibility Model by Latoschik and Wienrich [17] redesigned by authors.

Consequently, the question arises as to what influences the perceived plausibility of an XR application and what influence this has on other qualia. A promising research approach to investigate plausibility itself is breaks in plausibility. They can be caused by incongruencies within an XR environment. More recent studies made use of such incongruencies to better understand the role of plausibility [2, 3, 32]. These breaks in plausibility are seen as an analogy to breaks in presence. Breaks in presence are seen as one-time events during an XR exposure that participants can recover from [30]. However, the used incongruencies, which should cause breaks in plausibility, are continuous during the experiment. Therefore, participants experience them again and again, and perceived plausibility is permanently affected. Following this, a break in plausibility is defined as a significant difference in the perceived plausibility between the control and manipulated conditions.

Most recently, Brübach et al. [3] systematically evaluated different ways to cause such breaks in plausibility in VR. They tested four different manipulations within a VR bowling environment: familiar size, sound, object placement, and light. In the familiar size condition, the bowling ball seemingly remained the same size no matter how far away or close it was to the participant. In the sound condition, the sound of the rolling ball got louder the further away it rolled. In the object placement condition, benches and plants changed their position anytime they were not in the participant's field of view. Lastly, in the light condition, the reflections of the lights illuminating the bowling lane were manipulated. Their results show that only the manipulation of the familiar size was able to cause a break in plausibility. The other three manipulations did not cause a measurable break in plausibility. While they did not find an overall presence effect, results showed that the object placement manipulation showed significant effects on all three subscales of the presence questionnaire. However, this manipulation was noticed the least out of all manipulations. The authors suggest that participants knew something was manipulated but could not find it. They, therefore, paid more attention to the environment, which caused a stronger feeling of presence. The study by Brübach et al. [3] poses the first systematic evaluation of incongruencies, which can be used to cause a break in plausibility. The proposed incongruencies are, therefore, a good basis for further experiments looking at the effect of plausibility in virtual reality. However, only one of the incongruencies was detected consistently by the participants. It will be interesting to see if an expanded FoV could improve this.

In light of recent discussions regarding influencing factors in XR, it would be interesting to see how a peripheral display extension, like the one proposed by Xiao and Benko [33], influences qualia, like presence, spatial presence, and plausibility. Especially since previous experiments regarding these factors, in particular, often used high-resolution displays. As the paper was published in 2016, it is also interesting to see if the issues regarding performance still persist with the recent hardware improvements.

2.3 Summary and Contribution

Previous work has shown that the FoV significantly affects important XR user experience factors, like presence, virtual reality sickness, or spatial presence. With the rising attention to plausibility in XR, it is interesting to see which influence the FoV has on it. However, there is a lack of targeted research on how the FoV affects the user's perceived plausibility in XR. As we have seen, a wider FoV increases situational awareness [33]. Therefore, the user is more aware of the environment, possible changes in it, and potential disruptive factors. So, it is of particular interest whether an extended FoV can lead to increased perceived plausibility and, conversely, amplify breaks in plausibility. Previous work that examine plausibility and its effect on other qualia use incongruencies to cause a break in plausibility and measure the effect. In our study, we want to try to intentionally enhance the participant's focus on plausibility by the use of the peripheral display extension, as it has already proved to have a positive effect on situational awareness. We think that a higher situational awareness might lead to a higher focus on the environment and scenario and, therefore, their perceived plausibility. In contrast, however, we also expect that the incongruences will have an even stronger impact on the perceived plausibility when the display extension is used.

We used the experiment by Brübach et al. [3] as a basis for our two studies. They showed that the familiar size manipulation, where the bowling ball does not seem to change its size, no matter how far it is from the observer, was able to cause a measurable break in plausibility. So, we chose this manipulation as it was also highly likely to cause a break in plausibility in our experiment. The object placement manipulation, where objects changed their position when they weren't in the participant's field of view, was detected with the least accuracy in the previous experiment. We replicated this manipulation as we believe an extended FoV could increase spatial presence and situational awareness. Spatial Presence can be defined as a feeling of users to be located in a mediated space. When feeling spatially present, users often ignore the fact that these are technically generated environments. This could help the participants to better notice this incongruence. We omitted the other two manipulations to simplify our study design, as they did not show a significant effect in the previous study. To extend the participant's FoV, we built and implemented a peripheral display extension following the example of Xiao and Benko [33]. This extension was then integrated into a Vive Pro. We measured the perceived plausibility using the set of questions proposed by Brübach et al. [2] but modified them to fit our scenario better as proposed in Brübach et al. [3]. Additionally, presence and spatial presence were measured to see if they were affected by the display extension.

Our results can give insights into how an extended FoV influences the perceived plausibility in XR, whether a wider FoV can increase the perception of incongruencies in a VR environment, whether an enhancement of plausibility is possible, and whether results are in line with the CaP model, which can contribute to the further validation of the model.

2.4 Hypotheses

Previous studies suggest that a wider FoV positively impacts presence and spatial presence. It was also shown that breaks in plausibility caused by incongruencies do not necessarily influence presence or spatial presence. Therefore, the incongruencies' influence can be disregarded for presence and spatial presence. Thus, our first two hypotheses are as follows:

- **H1** Presence is higher with the peripheral display extension than without.
- **H2** Spatial presence is higher with the peripheral display extension than without.

As a wider FoV can increase situational awareness, incongruencies should be perceived more strongly. Consequently, the extension should lead to stronger breaks in plausibility. This leads us to our next hypothesis:

- **H3** The perceived plausibility in the incongruence conditions should be significantly lower with the peripheral display extension.

There is mixed research on the effects of a wider field of view on VR sickness. As we use the same method to extend the FoV as Xiao and Benko [33], we expect similar results. They showed that the sparse peripheral display was able to reduce VR sickness. So, our last hypothesis is as follows:

- **H4**: The peripheral display extension does not increase VR sickness.

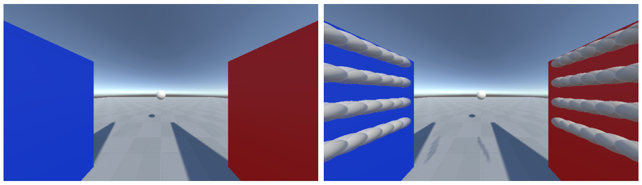
3 PERIPHERAL DISPLAY EXTENSION

3.1 Hardware

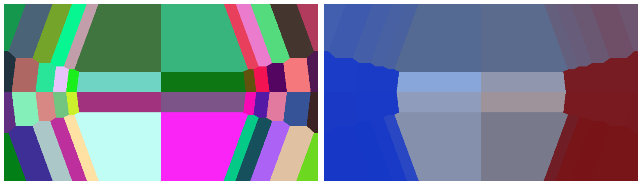
The components for the display extension were selected based on the previous prototype from Xiao and Benko [33]. We decided to use the Arduino Nano Every, powered by a 6m USB cable needed for the UART connection. A special casing for the Arduino was designed to attach it to the headset.

We chose WS2812S LED strips with a density of 144 LEDs per meter. The LEDs are powered by a 5V DC power supply unit rated at 25 W. Within the HTC Vive was a 5 x 5 cm space where the LEDs could be placed. This allowed for 4 rows of 6 LEDs each. After the strips were connected, they were glued onto a 3D-printed backplate so they could be easily placed into the headset.

Even at just 10% brightness, the LEDS were too bright and caused harsh reflections on the HMDs lenses (see figure 1b left). A thin plate of semi-see-through material was designed and printed to counteract this. It was placed over the LEDs to dim their light and



(a) View of the extra camera. **(b) View with visible lightprobes.**



(c) Individual areas of the calculated Voronoi diagram. **(d) Actual colors assigned to the lightprobes.**

Figure 3: Process of calculating the color for each lightprobe using the Voronoi diagram.

reduce reflections (see figure 1b right). This also ensured that the LEDs were not significantly brighter than the HMD displays. The display extension was installed into the HTC Vive. The cables were tucked away behind the face cover of the HMD. The Arduino was installed on the head strap using its case. The USB and power cable were attached to the existing HTC Vive cable with zip ties to avoid tangling.

3.2 Software

We slightly adapted the approach by Xiao and Benko [33] in our implementation. We used only one extra camera attached to the player's head, which targets both eyes. It has a FoV of 120° and renders the scene with a 256 x 144 pixels resolution. We also used lightprobes, which were represented by spheres. Their placement can be seen in figure 1a. A Voronoi diagram is calculated for the extra camera view when the application is first started. It assigns each pixel in the additional camera view to the closest lightprobe. The colors of all pixels assigned to one lightprobe are then averaged and result in the color for the lightprobe and, therefore, the corresponding LED. This is done only once in the beginning, as the position of the lightprobes in relation to the camera view does not change over time. To ensure that the color of the lightprobe itself does not influence the color calculation, they were hidden using a culling mask. Figure 3 shows a visual representation of the process performed to calculate the colors of the lightprobes.

A serial connection is used to send the calculated color values to the Arduino. Data transfer to the Arduino is done in a Unity coroutine using a byte array of RGB values. However, the LEDs began to flicker when they were first tested with the highest possible framerate of 100 Hz. To avoid flickering, it was decided to reduce the refresh rate of the peripheral display to 10 Hz by calling the coroutine less often, as the rapid change of colors in the LEDs was probably the reason for it. This reduction has meant that the flickering has stopped.

The FastLED library was used to set up the Arduino. This involved starting the serial connection to Unity, configuring the LED type, data pins, and RGB array, and setting LED brightness to 10%. Color values from Unity were directly read into the Arduino byte array, combined into RGB values, and then transmitted to the LEDs.

All 3D models, building instructions, a list of used materials, and the source code will be publicly available here: Unity Code & Arduino Code.

3.3 Apparatus

The application ran on a high-end computer with a Nvidia Geforce RTX 4070 Ti GPU and an Intel i9-13900K CPU with 64 GB of RAM. The application was developed in the Unity Engine (v2021.3.14f1) using the Steam VR Plugin (v2.7.3). We used the HTC Vive Pro headset in combination with the Valve Index controller to ensure a more natural interaction with the application.

The latency between the Unity application and the LEDs was measured manually by counting frames. For this purpose, a video was recorded with a 240fps camera that shows the color changes within the scene and the color change of the LEDs. The latency was 35 ms on average, which is sufficient for a standard VR application [4, 31].

4 METHODS

4.1 Study Design

We used a randomized 2 x 3 within-subject study design. The participants are distributed into different conditions with a randomized list independent of demographic data. The demographic distribution across the conditions showed no significant differences.

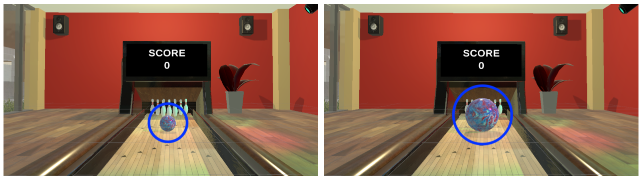
The first factor *FoV* is divided into the normal FoV (90°) of the headset and the extended FoV (120°) through the peripheral display extension. The same headset was used for both conditions and the LEDs could simply be turned off for the normal FoV condition. The second factor is the *incongruencies*. There are two different incongruencies and a control scene. We used a *familiar size* incongruence as it had the strongest effect in a previous experiment. The second incongruence was the *object placement* within the scene.

4.2 Application

We adapted the environment and bowling task from Brübach et al. [3]. It consisted of a single bowling lane, a ball dispenser on the left, a window front with a simple outside view, and decorations like benches, plants, and lights. Contrary to the environment of Brübach et al. [3], we colored two of the walls red. This was done to create a stronger color difference between the walls, ceiling, floor, and the outside view. The environment can be seen in figure 1a.

For the *familiar size* incongruence, the bowling ball remained the same size in the perception of the participant. To achieve this, the ball was scaled up in relation to its distance from the participant (figure 4). For the *object placement* incongruence, the benches and plants changed between three fixed positions every time they were not in the direct FoV of the participants. Of course, they changed when they were still visible with the display extension. They disappeared in one location and then reappeared in a different one (figure 5).

Participants were able to pick up the ball and throw it using the Valve Index controller, allowing them to let go of it completely when throwing the ball, resulting in a more natural interaction.



(a) Familiar Size Congruent **(b) Familiar Size Incongruent**

Figure 4: Familiar Size Manipulation

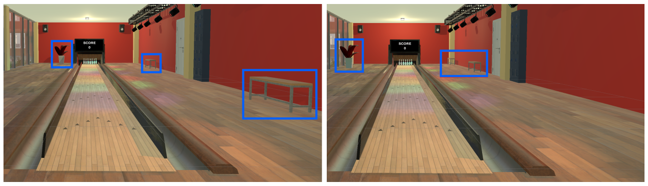


Figure 5: Object Placement Incongruence

They could use either hand to pick up and throw the ball. Guards on each side of the lane prevented the ball from missing the pins. A barrier came down after the ball hit the pins, and the pins were reset. The ball then came back up in the ball dispenser. Participants had to throw the ball eight times in each condition.

A simple tutorial was implemented to familiarize participants with the interaction. Practicing was particularly important for participants with little to no experience with VR or the Valve Index controller. A simplified scene was used to avoid priming the participants. The LEDs were turned off during the tutorial.

4.3 Measures

We used a variation of the perceived plausibility questionnaire (PPQ) by Brübach et al. [2] to measure the perceived plausibility. As in Brübach et al. [3] the word "object" was also replaced with the word "scenario". This questionnaire has thirteen items on a 7-point Likert scale ranging from *I do not agree at all (1)* to *I fully agree (7)*. The questions can be found in Table 1.

Table 1: Questions regarding the perceived plausibility proposed by Brübach et al. [3].

no	question
1	I am used to a scenario behaving this way.
2	In everyday life, I expect the scenario to behave this way.
3	I have seen the scenario behave this way in real life.
4	The behavior of the scenario is unusual for me. [1]
5	I do not know the behavior of the scenario from real life. [1]
6	I had a prior expectation of how the scenario would behave.
7	I expected the behavior of the scenario.
8	I have seen this scenario behavior in movies, games, etc. before.
9	I was surprised by the behavior of the scenario. [1]
10	I had no idea that the scenario will behave this way. [1]
11	The behavior of cause and effect matched the scenario.
12	The behavior of the scenario made sense.
13	I think this behavior of the scenario is impossible. [1]

[1] Question is inverted.

The Igroup Presence Questionnaire (IPQ) by Schubert et al. [23] was used to measure presence, with three subscales: *spatial presence* (five questions), *involvement* (four questions), and *experienced realism* (four questions), as well as one item that does not belong to a subscale. The questionnaire has fourteen items on a scale from 0 to 6. The wording of the endpoints varies between the questions.

The Spatial Presence Experience Scale (SPES) by Hartmann et al. [14] was used to measure spatial presence. It has the subscales *self-location* and *possible action* with four questions each. The items are on a scale from *I do not agree at all* (1) to *I fully agree* (5).

To control participants' workload during the experiment, the NASA-TLX by Hart et al. [13] was used. It has six subscales: *mental demand*, *physical demand*, *temporal demand*, *performance*, *effort*, and *frustrations*. The items are measured on a scale from 0 to 100.

We used the Virtual Reality Sickness Questionnaire (VRSQ) by Kim et al. [16] to control for VR sickness. It measures sickness caused by virtual reality with the two dimensions *oculomotor* and *disorientation*. It has five items for *disorientation* and four items for *oculomotor* on a scale from *not at all* (0) to *strong* (3) to describe the symptoms.

After each condition, we asked participants whether they noticed a manipulation in the scene and, if so, what they thought was manipulated.

As there is no standardized questionnaire to measure the effects of the LEDs, we came up with our own questions. At the end of the experiment, we asked the participants five questions about their experience with the LEDs. They can be seen in table 2. The questions were on a 5-point scale ranging from *not at all* to *very much*. Additionally, we asked them if they experienced negative effects from the LEDs and, if so, to describe them. Lastly, we asked if participants liked the expansion or the normal display better or if they had no preference.

4.4 Procedure

The entire procedure is also shown in figure 6. Initially, participants read and signed the experiment information and the consent forms. They then filled out the demographical data and information about their previous VR experience. Then, they were verbally told how the interaction with the environment worked before entering the tutorial scene in VR, where they could familiarize themselves with the interaction. After the tutorial, they filled out the pre-VRSQ before the actual experiment started. They started with the first condition, where they threw the bowling ball 12 times. Next was the questionnaire phase, where they answered the PPQ, IPQ, VRSQ, and open questions about whether they detected a manipulation and, if so, what it was. These two phases were repeated six times, once for each condition. After the last questionnaire block, they were also asked about their experience with the LEDs and their preferences. The experiment ended with the participants being informed about the purpose of the study and manipulations.

4.5 Experiment 1

4.5.1 Participants. Thirty participants took part in experiment 1. They received a student credit for their participation. The pool was divided into 26 female and 4 male participants. The age ranged from 19 to 25, with a mean age of $M = 21.13$ ($SD = 1.53$). All participants

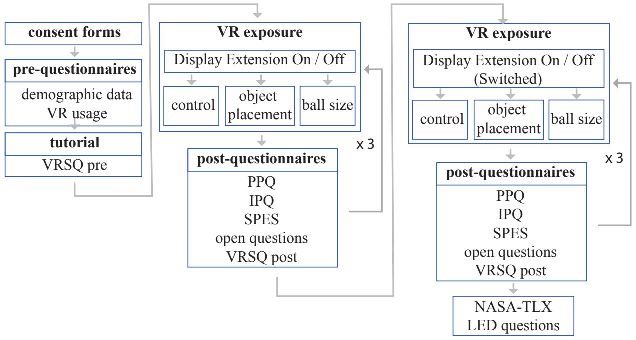


Figure 6: Schematic representation of the experiment procedure with pre- and post questionnaires and six VR conditions.

were university students at the time of the experiment. Three had none to one hour of VR experience, fifteen had one to three hours of experience, eight had three to five hours of experience, three had five to ten hours of experience, and one participant had ten to twenty hours of experience.

4.5.2 LED Questions. As we can see in table 2, most participants did not think that the LEDs enhanced their experience. Only about a sixth of the participants reported that the LEDs were helpful. Nine participants reported negative effects from the LEDs. The main complaint was that the LEDs were too distracting and too bright. Similarly, only seven participants liked the condition with the display extension more, seven had no preference, and sixteen preferred the application without the LEDs.

4.5.3 Results Experiment 1. Looking at the results, we found a significant interaction effect in the presence or spatial presence scores. Both were significantly higher in the familiar size condition than the control condition. However, it was only for the normal FoV condition. We did not find a significant effect for the FoV condition. This is in line with the previous results from Brübach et al. [3].

The results show that the familiar size manipulations caused a break in plausibility since the perceived plausibility was significantly lower than in the control condition. We did not find a significant effect for the object placement condition. As in the previous experiment, the object placement manipulation was too subtle to notice. While almost half of the participants correctly identified the familiar size manipulation, only two identified the object placement manipulation.

We found no significant difference in the VRSQ between the conditions with and without the peripheral display extension. Overall, there is no evidence that the application caused VR sickness.

Looking at the questions regarding the LEDs in the end, we can see that almost one-third of the participants experienced negative effects from the peripheral display extension. Participants' main concern was that the LEDs were too bright and would distract them from the actual VR scene.

In summary, the biggest issue with the experiment was that the object placement incongruence was not detected consistently enough. To be recognized better, it should be strengthened in the next experiment. Another issue is the negative effects that some participants experienced from the LEDs. Changes to the implementation should mitigate or even eliminate these. To address these issues, we conducted another user study.

4.6 Experiment 2

4.6.1 Changes After Experiment 1. We used the same application, measures, and procedure for experiment 2 as for experiment 1. We did, however, make adjustments to the *object placement* manipulation. As with the previous experiment by Brübach et al. [3], this incongruence seemed to be too subtle to be recognized by the participants reliably. Therefore, we tried to strengthen it for experiment 2. Previously, the objects just disappeared from their previous location and appeared in their new spot. Now, the objects would slide from one place to another. This causes a continuous change in the LED's color representing the movement, making it easier to see the movement via the display extension.

In experiment 1, almost a third of the participants experienced negative effects from the LEDs. To address this issue, we lowered the brightness of the LEDs to 5%. We also changed the framerate from 10 Hz to 40 Hz. A higher framerate would have resulted in LED flickering. Another issue with experiment 1 was the participant pool, which consisted exclusively of young, mostly female students. This was partly due to the compensation method (student credit for a study program with a high percentage of female students) in experiment 1. So, for experiment 2, participants could receive compensation equivalent to USD 18 in the currency of the country where the experiment was conducted. This makes it possible for non-students to participate in the experiment, which should result in a more diverse sample.

4.6.2 Participants. Thirty persons participated in the experiment. Three had to be excluded due to technical difficulties, leaving 27 for the data analysis. Eighteen participants were female, and nine were male. The age ranged between 18 and 62 with a mean age of $M = 28.74 (SD = 9.80)$. Most participants were students, with a total of nineteen; five were employees, two were currently not employed, and one was a pupil (over 18 years old). The experience with VR varied across the participants, with six having none to one hour of VR experience, twelve having one to three hours of experience, three having five to ten hours of experience, five participants having ten to twenty hours of experience, and one had more than twenty hours of VR experience.

4.7 Results

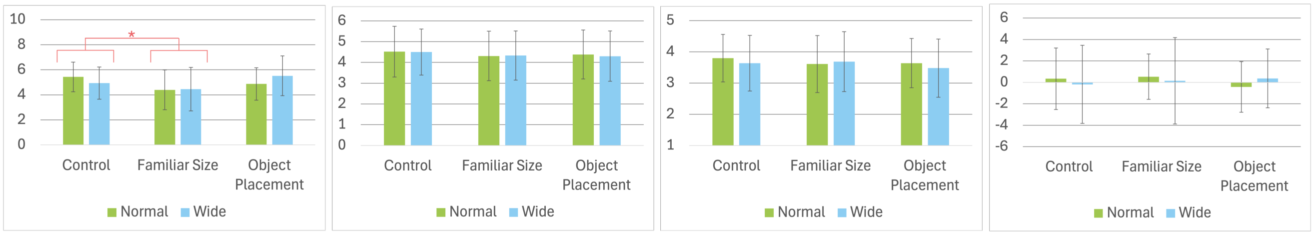
In some cases, the assumption of sphericity was violated. The appropriate correction was applied wherever this was the case. All means, and standard deviations for each condition and questionnaire can be seen in figure 7.

4.7.1 Control Variables. As in experiment 1, the NASA-TLX was only measured once at the end. The overall average was 31.76. We did see a higher score in the performance (60.11). However, based on the participants' comments, this was probably due to their poor performance in bowling, which was not evaluated. Overall, as with experiment 1, we don't think that these scores indicate an influence on other measurements or indicate a too-high task load.

Table 2: Results of the LED questions for experiments 1 and 2 in total numbers.

	To what extent did the expansion of the FoV by the LEDs help the virtual environment feel authentic and believable?	Were you able to perceive more details in the virtual environment due to the expanded FoV provided by the LEDs?	Did you feel that the expansion of the FoV by the LEDs helped the virtual environment feel true, real, and believable?	To what extent did the expansion of the FoV by the LEDs help the virtual environment feel true and real to you?	Did the expansion of the FoV through the LEDs actually make you feel immersed in the virtual environment and present in a real environment?
Experiment 1					
Experiment 2					

🟥 Not At All 🟧 A Little 🟨 Neutral 🟦 Much 🟩 Very Much



(a) Perceived Plausibility (b) Presence (IPQ) (c) Spatial Presence (SPES) (d) VR Sickness (VRSQ)

Figure 7: Means and standard deviation for each condition and questionnaire for experiment 2. The red star marks significant results.

In experiment 2, seventeen participants detected the familiar size incongruence in the normal FoV condition and fifteen in the wide FoV condition. Only seventeen participants recognized the object placement incongruence in the normal FoV condition and sixteen participants in the wide FoV condition. This shows that the change in the object placement incongruence led to an increased detection rate.

4.7.2 Perceived Plausibility. We calculated Cronbach's α to check the internal consistency. We used the answers of the 27 participants for all six conditions, resulting in 162 answers for the data analysis. For the 13 questions, Cronbach's α is .96, which also indicates a high internal consistency.

The ANOVA showed a significant main effect for the incongruencies ($F(1.64, 42.66) = 4.73, p = .019, \eta_p^2 = .154$). There was no significant main effect for the FoV ($F(1, 26) = 2.29, p = .142, \eta_p^2 = .081$) and no interaction effect between FoV and incongruencies ($F(1.51, 39.35) = .88, p = .397, \eta_p^2 = .033$).

Post-hoc tests using the Holm correction showed that the significant effect is between the familiar size and the control condition ($p_{holm} = .011$), with a higher perceived plausibility in the control condition. There was no significant effect between the object placement condition and both the control condition ($p_{holm} = .109$) and the familiar size condition ($p_{holm} = .291$).

4.7.3 Presence. We found no significant main effects in the IPQ for the FoV ($F(1, 26) = 0.07, p = .790, \eta_p^2 = .003$) and the incongruencies ($F(2, 52) = 0.58, p = .096, \eta_p^2 = .086$). There was also no significant interaction effect between the two conditions ($F(1.60, 41.53) = 0.26, p = .720, \eta_p^2 = .010$).

4.7.4 Spatial Presence. We found no significant main effects in the SPES for the FoV ($F(1, 26) = 1.33, p = .259, \eta_p^2 = .049$) and the incongruencies ($F(2, 52) = 1.83, p = .171, \eta_p^2 = .066$). There was also no significant interaction effect between the two conditions ($F(2, 52) = 2.52, p = .090, \eta_p^2 = .088$).

There were also no significant main effects in the *spatial presence* subscale of the IPQ for the FoV ($F(1, 26) = 0.55, p = .465, \eta_p^2 = .021$) and the incongruencies ($F(2, 52) = 1.71, p = .190, \eta_p^2 = .062$). There was also no significant interaction effect between the two conditions ($F(2, 52) = 1.08, p = .346, \eta_p^2 = .040$).

4.7.5 Virtual Reality Sickness. We did not find a significant main effect or interaction effect in the VRSQ for both the FoV ($F(1, 26) = 0.01, p = .928, \eta_p^2 < .001$) and the incongruencies ($F(1.53, 39.7) = 0.17, p = .783, \eta_p^2 = .007$). There was also no interaction effect between the two conditions ($F(2, 52) = 0.59, p = .557, \eta_p^2 = .022$). As in experiment 1, we therefore assume that there was no significant difference in the VR sickness between the conditions or over time.

4.7.6 LED Questions. Again, the majority of the participants did not think that the LEDs enhanced their experience, as we can see in table 2. Only about a sixth of the participants reported that the LEDs were helpful. Eight participants reported negative effects from the LEDs. This time, the main complaint was that the LEDs were too distracting. In line with this, eleven participants reported that they preferred the application without the extension, while ten had no preference, and only six preferred the application with the LED extension.

5 DISCUSSION

We have to reject hypotheses H1, "Presence is higher with the peripheral display extension than without.", H2, "Spatial presence is higher with the peripheral display extension than without.", and H3, "The perceived plausibility in the incongruence conditions should be significantly lower with the peripheral display extension.". We could not find any significant main effects for presence or spatial presence, neither for the manipulations nor the LED factor. We also did not find significant interaction effects.

We did find a significant effect for a break in plausibility for the familiar size manipulation. However, as with experiment 1, not for the object placement manipulation. And again, the peripheral display extension did not seem to have any effect on the perceived plausibility. Even though this time, more than half of the participants identified both manipulations correctly.

H4 *The peripheral display extension does not increase VR sickness.* can be accepted. We found no significant effect in the VRSQ scores. Previous work by Xiao and Benko [33] found that display extensions could even see a reduction in VR sickness compared to the normal condition. In our study, the overall VR sickness was quite low (mean value < 1 in all conditions). Therefore, VR sickness could hardly be reduced, resulting in non-significant differences between normal and wide FoV conditions. This also aligns with Lubos et al. [20].

As in experiment 1, about a third of the participants had negative effects from the LEDs. Even though we lowered the brightness, they were still perceived as too distracting. This could be due to the increased refresh rate of 40Hz compared to the 10Hz.

As our rejected hypotheses show, we could not confirm all of Xiao and Benko's results [33]. We can confirm that the peripheral display extension did not cause VR sickness. However, we could not find evidence that it helped with VR sickness, as the total VR sickness scores do not indicate VR sickness in any condition.

We could not find an increased presence or spatial presence when using the extended FoV condition. While we did see a reduced presence and spatial presence in experiment 1 for the familiar size incongruence, this was only true in the normal FoV condition. This might be due to the nature of our display extension. In contrast to previous experiments, which used high-resolution projection displays, we used a low-resolution solution with 24 LEDs per side. It would be interesting to compare our low-resolution display extension with an HMD with a wider FoV at a higher resolution.

As for the incongruencies, we can confirm the results from Brübach et al. [3]. Here, we can see that the familiar size incongruence was able to cause a break in plausibility while the object placement incongruence could not. The object placement incongruence specifically relied on peripheral information to be noticed. While in experiment 1, only two participants noticed the incongruence it was almost half of them in experiment 2. Nonetheless, this incongruence did not significantly affect the perceived plausibility. This leads us to the conclusion that this incongruence might not be suitable to cause a break in plausibility.

In experiment 1, it seems like the break in plausibility had an influence on presence and spatial presence. However, not in experiment 2. In experiment 2, though, the standard deviation was higher than in experiment 1. The tendency that the familiar size incongruence caused a lower presence and spatial presence rating stayed the same. We believe that a larger sample might reveal a clearer tendency or even a significant effect. Then, the findings of both experiments would be in line with the result of the previous experiment by Brübach et al. [3].

5.1 Limitations and Future Work

One evident limitation of our prototype is the significantly lower refresh rate of the peripheral display extension at 10 and, respectively, 40Hz compared to the high-resolution main display of 90Hz. A higher refresh rate led to flickering of the LEDs in our prototype and increased the latency. This is probably due to the calculation of the colors. A more efficient calculation method and a smoothing function, instead of harsh color changes, could help with this.

Almost a third of all participants experienced negative effects from the LEDs. Their main concern was that they were too bright and thus distracting from the main environment. The brightness of the LEDs was reduced from 10% to 5% in experiment 2. However, this still seemed to be too bright. Lowering the brightness even more, however, would lead to distorted colors. One way this could be addressed would be to switch to different LEDs. Another way would be to make the dimming plate even thicker.

As always, a within-subject design has its limitations. As the manipulations were the same for both LED conditions, participants who correctly identified them in the first round could probably recognize them more easily in the second round. We tried to reduce this effect with a randomized order. In general, the sample size might have been too small. Maybe a larger third study that addresses the raised issues would find different results.

Lastly, our sample size of 30 participants was quite small for the effects we would like to measure. A higher sample size might reveal different results.

6 CONCLUSION

While a higher FoV can bring many benefits, it also carries risks. Many previous studies in VR have only looked at a reduced FoV versus a normal FoV. A wider FoV has often been used in immersive, non-VR environments. However, these are mainly high-resolution displays. We were interested to see if a simple peripheral display extension with a resolution of 4 x 6 LEDs could have the same effect. For this purpose, we built a peripheral display extension into an HMD. We also looked at what influence this extension has on perceived plausibility. Incongruencies were introduced, which should influence the perceived plausibility. We then tested this in a VR bowling environment with two studies. The results show that the extension did not lead to increased VR sickness but also could not create a higher sense of presence and spatial presence like high-resolution displays. Furthermore, it did not influence perceived plausibility. The incongruencies were able to affect perceived plausibility in the normal FoV condition. The effects only occurred for the familiar size incongruence, not the object placement. We were, therefore, able to confirm that familiar size is a suitable incongruence to cause a break in plausibility.

ACKNOWLEDGMENTS

This research has been funded by the Bavarian State Ministry for Digital Affairs in the project XR Hub (project number A5-3822-2-16).

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