Luminance and Color Correction for Display Stitching in Semi-Cave Virtual Reality

Dariusz Sawicki[1][a], Łukasz Izdebski[1], Agnieszka Wolska[2][b] and Mariusz Wisełka[2][c]
[1]*Warsaw University of Technology, Institute of Theory of Electrical Engineering, Measurements and Information Systems, Warsaw, Poland*
[2]*Central Institute for Labour Protection, National Research Institute (CIOP-PIB), Warsaw, Poland*

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Abstract: The most spectacular example of a virtual reality (VR) environment is Cave (Cave Automatic Virtual Environment). Image stitching is an essential problem encountered in displaying images in the Cave VR. We analyzed this problem in the Semi-Cave installation, a low-budget representative of the Cave VR. Seamless stitching of displayed images requires two independent tasks: geometrical correction and color/luminance correction. The aim of this work is to present the main aspects and the methods used for color/luminance correction for seamless stitching of displayed images in the Semi-Cave installation. The proposed procedure and the software developed for color correction of images were tested and verified. The final effect of displaying stitched images was subjectively assessed. The impression of immersion into the Semi-Cave VR was sensed by subjects, and in this way, the correctness of the proposed method was confirmed.

1 INTRODUCTION

The quality of the displayed images is a key issue in Cave (Cave Automatic Virtual Environment) that determines the correctness of immersion into the created VR environment. Immersion into the VR is understood as a specific concept that defines how well the VR environment represents the real world and how well it is perceived (Slater, 2003). The following parameters are considered as the most important in the immersion process: correctness of color and image geometry in the stitched images, correctness of the color rendering process, perception of projection, and image resolution (Slater, 2003).

Image stitching is an essential problem encountered in displaying images in the Cave VR installation, as well as in many other multimedia applications. We analyzed this problem in the Semi-Cave, a low-budget representative of the Cave VR installation. Image stitching in the Semi-Cave installation requires two independent corrections: geometric correction which is the first task and described in the work (Sawicki et al., 2018); and color/luminance correction—assuming that the images are already geometrically corrected.

The need to correct the color of the stitched images in the Semi-Cave installation results from the differences in the colors of the displayed images. This is mainly related to the differences in image displaying by particular projectors (individual differences and aging of the equipment). The difference in color coordinates is a measure of the color mismatches (Mokrzycki and Tatol, 2011).

The problem encountered in seamless stitching of images to create a panorama is well described in the literature (Singh and Saravanan, 2017, Pravenaa and Menaka, 2016). Geometric correction and color correction work together in most of the stitching methods for creating panoramas (Pravenaa and Menaka, 2016). Nevertheless, advanced methods of color correction are applied in such cases (Bellavia and Colombo, 2018). Color stitching for the Semi-Cave VR requires not only an advanced color correction method but also solving additional measurement problems that we would like to highlight here.

[a] https://orcid.org/0000-0003-3990-0121
[b] https://orcid.org/0000-0003-3912-605X
[c] https://orcid.org/0000-0002-7145-6457

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The aim of this paper is to present the main aspects of color/luminance correction and the procedure used for color correction for seamless stitching of images in the Semi-Cave installation.

2 TECHNICAL ASPECTS AND PRELIMINARY ANALYSIS

The Semi-Cave was implemented in a rectangular room, measuring 8.6 m × 4.3 m × 6 m. The image was created by direct projection onto the four walls of the room. Image creation was ensured by six projectors (Canon, XEED WUX400ST) presented in Figure 1.

In the computer system responsible for image control, three graphic cards (NVidia GTX 980 Strix OC SLI) were used. Each of the graphic cards supported two projectors. The whole system ensured a smooth and sharp display of images at a resolution of 1920 × 1080. The details of the installation are described in the work (Sawicki et al. 2017).

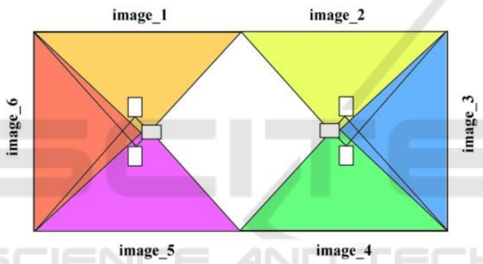

Figure 1: Arrangement of projectors in the Semi-Cave laboratory (Sawicki et al., 2018).

The way in which the images are displayed in Semi-Cave strongly influences the possibilities of geometric and color corrections. Stitching of images should be done differently on the same wall (e.g., Image_1 and Image_2 in Figure 1) and on neighboring walls, respectively (e.g., Image_2 and Image_3 in Figure 1). In the first case, for the correct display and ease of correction, it is convenient to use overlapping images. For geometric correction, an overlapping part with a width of 50 pixels is considered. In the second case (in the corner of the room), the images are corrected at the place of "contact" (i.e., at the edge of the wall corner). If one subsystem of display correction works for geometry as well as for color, the adopted rules must be applied in both the cases. As a consequence, the color needs to be equalized in the overlapping part. This problem does not occur in the case of geometry correction—the reproduction of properly corrected fragments in the same place does not affect the geometry, but changes the luminance or color.

On the basis of the analysis of the entire correction process (geometric and color correction), we assumed that the geometry correction should be performed as the first task. This is due to the fact that it does not require additional measurements but only the visual assessment of corrected and displayed images. However, color/luminance correction requires taking measurements during correction.

3 COLOR SPACE USED IN SEMI-CAVE

The projectors used enable working in many different modes (Canon User's Manual, 2013). However, the manufacturer declares compliance with the sRGB space only for the Photo/sRGB mode.

The sRGB color space is defined in the IEC standard (IEC 61966-2-1:1999, 1999). Linearization (gamma) dependencies for each coordinate (R, G, B) are described by equations (1)–(4). Due to the additivity of the color components of radiation, the corresponding dependence will also apply to the black–white scale (BW—the scale of gray levels).

for $R_L,G_L,B_L \leq 0.0031308$

$$\begin{cases} R = 12.92 \cdot R_L \\ G = 12.92 \cdot G_L \\ B = 12.92 \cdot B_L \end{cases} \tag{1}$$

for $R_L,G_L,B_L > 0.0031308$

$$\begin{cases} R = 1.055 \cdot (R_L)^{1/2.4} - 0.055 \\ G = 1.055 \cdot (G_L)^{1/2.4} - 0.055 \\ B = 1.055 \cdot (B_L)^{1/2.4} - 0.055 \end{cases} \tag{2}$$

for $R,G,B \leq 0.04045$

$$\begin{cases} R_L = R/12.92 \\ G_L = G/12.92 \\ B_L = B/12.92 \end{cases} \tag{3}$$

for $R,G,B > 0.04045$

$$\begin{cases} R_L = ((R + 0.055)/1.055)^{2.4} \\ G_L = ((G + 0.055)/1.055)^{2.4} \\ B_L = ((B + 0.055)/1.055)^{2.4} \end{cases} \tag{4}$$

Where $R,G,B \in [0,1]$ and $R_L,G_L,B_L \in [0,1]$. R,G,B are the color coordinates that define a color in the sRGB space, for example, for gray scale from black

(R=G=B=0) to white (R=G=B=1), while R_L,G_L,B_L are the luminance coordinates of the displayed image.

The dependence between the image luminance and control parameters (stimulation) in monitors is described by the power function. At the same time, the dependence of the brightness of the perceived image is also not linear and can be described by a similar function—the perceptual dependencies of the sense of sight of humans are described by the Weber–Fechner's law (Bruce, 2014). Hence, the mathematical description of nonlinear dependencies (1)–(4) is an attempt to match the technological properties of the equipment to the perceptual abilities of the human. The assumption of an appropriate function describing the nonlinear relations very strongly affects the perception of differences. In the software used for controlling graphic devices as well as for processing images and computer graphics, the coordinates R,G,B are most often expressed in a binary form (2^{bit_depth}-1). For example, for *bit_depth* = 8 the coordinates change in the range of [0,255]. This requires rescaling from the binary form to the form expressed in formulas (1)–(4) or vice versa.

It is worth noting that according to the IEC standard (IEC 61966-2-1:1999, 1999), the power in equations (2) and (4) has a value of 2.4 instead of 2.2, that is, the value assumed to be typical in the gamma correction of PC hardware (Poynton, 2005, Poynton, 2012). In practice, the approximate formulas (5) and (6) are most often used.

for $R,G,B \in [0, 1]$ and $R_L,G_L,B_L \in [0, 1]$

$$\begin{cases} R = (R_L)^{1/2.2} \\ G = (G_L)^{1/2.2} \\ B = (B_L)^{1/2.2} \end{cases} \quad (5)$$

$$\begin{cases} R_L = (R)^{2.2} \\ G_L = (G)^{2.2} \\ B_L = (B)^{2.2} \end{cases} \quad (6)$$

4 MEASUREMENTS AND PERCEPTUAL IDENTIFICATION OF COLOR DIFFERENCES IN SEMI-CAVE

A Chroma Meter CS-200 instrument (Konica Minolta (Chroma Meter CS-200, 2013) was used to measure the luminance and color of the displayed images. The instrument is adjusted to V(λ)—the relative spectral luminous efficacy of the eye adapted to brightness. This allows the direct measurements of luminance and X,Y,Z color coordinates in the CIE XYZ color space. However, it does not allow color correction for usage in the display software. In addition, the luminance values of the displayed images in Semi-Cave are at a low range (below 60 cd/m^2), which further reduces the usefulness of this type of measurement in color correction.

A number of experiments were carried out which confirmed that the X,Y,Z color coordinates cannot be determined directly in an efficient and useful way. Ultimately, a decision was made to carry out the measurements and color correction indirectly and independently for each R, G, and B component. In this case, the measured luminance value will indeed take into account the curve V(λ). This is enough to compare the image fields displayed by the neighboring projectors, but within only one component. The display correction will be based on the determined difference. This will allow displaying identical colors regardless of how the projectors display them. On the other hand, this means treating the entire displaying process (software, graphic cards, projectors, wall reflectance) as a "black box." We know the input parameters (binary values describing the color of an image), which are defined in the software and are subject to color correction, and the output parameters (information displayed on the Semi-Cave wall), which are subject to measurement. The aim of the correction software is to adjust the input parameters according to the changes needed in the output parameters and take the relevant measurements.

5 COLOR CALIBRATION IN SEMI-CAVE: ANALYSIS OF POSSIBILITIES

For system calibration, a set of color images was prepared in four groups: for each component R, G, B, and BW (gray levels). A comparison of all the images and their corresponding R,G,B color coordinates is summarized in Table 1. However, unfortunately, the changes in the color of low-luminance images cannot be actually recognized in a printout of this table—especially in the case of binary components R (31,0,0) and B (0,0,31)—due to limited printing capabilities.

The analysis of the results of the preliminary tests leads to quite interesting conclusions. On the one hand, the results are in line with expectations—with known perceptual properties of the human sight. A human cannot identify differences at a level of 1 bit (1/256 of the displayed full scale of color) for any component in the dark parts of an image. It is assumed that a human can distinguish a maximum of 60–90 shades of one color. In the bright parts of a picture, a human can distinguish the shades of red color better than the shades of blue, and in an exceptional situation of a specific color neighborhood, a difference at the level of 1 bit would be noticed. On the other hand, the measurements of luminance in many of the analyzed cases do not help in distinguishing the images. This is due to the reflection properties of the walls in the Semi-Cave. The use of reflective paint for a projector wall does not enable as high reflectance as a professional projection screen.

Table 1: The set of used images (*R*,*G*,*B* and BW—gray) with proper *R*,*G*,*B* binary coordinates.

R image binary coordinates	*G* image binary coordinates	*B* image binary coordinates	BW image binary coordinates
0,0,0	0,0,0	0,0,0	0,0,0
31,0,0	0,31,0	0,0,31	31,31,31
63,0,0	0,63,0	0,0,63	63,63,63
127,0,0	0,127,0	0,0,127	127,127,127
191,0,0	0,191,0	0,0,191	191,191,191
223,0,0	0,223,0	0,0,223	223,223,223
255,0,0	0,255,0	0,0,255	255,255,255

Color interpolation at a resolution of 1 bit for each component corresponds to the border perceptual and measurement possibilities of identifying color differences. The perceptual capabilities of a human do not allow identifying differences at such a resolution in the whole range of luminance that can be obtained while displaying images. Nevertheless, experiments have shown that under real conditions in the Semi-Cave, differences at a level of 1 bit may be noticed in specific displayed images.

Color correction means interpolation of the values of each color coordinate in a specific area of a displayed image. If the side edge of a displayed rectangle is the place of matching the common color, it can be assumed that the area on which the interpolation will be carried out will be a rectangle. Its height will be consistent with the height of the displayed image, with one edge being the edge of the match and the other edge determining the “depth of penetration” of interpolation in the area of the displayed image.

Two interpolation parameters need to be defined. The first is the “depth of penetration.” After conducting preliminary experiments, it was assumed that the interpolation would cover one-third area of the surface of the displayed image. This means that each image should be divided into three equal parts (left, central, and right). The luminance and color will not be modified in the central part, but will be modified in the area on the left side or right side where interpolation is associated with the left edge or right edge of the match, respectively.

The second parameter is the “type of changes” carried out in the value of the interpolated parameter. The simplest solution is to change linearly the values of color coordinates in the stitched images. The problem seems to be trivial: the color correction of stitched images is done in a large space and the differences in corrected colors are small. In such a large space, local, high color changes may occur—depending on the content of the image. Therefore, the differences related to color correction would not be noticeable. However, in many cases, we can see large surfaces with almost the same color—for example, the sky with a similar or the same blue color. In this situation, because of human perception, incorrect local color changes will be unnatural.

The simplest linear change is practically unfavorable in every case. Taking into account the results of studies on perception and measurement in real conditions, we assumed that the curve of color changes resulting from the correction should be smooth (in the sense of continuity of the first derivative). This is important because of lateral inhibition (Bakshi et al., 2017, Hall, 1989), a phenomenon that causes even the smallest local unevenness of changes in color or luminance to be emphasized and perceived by the sense of sight. It is worth considering the appropriate connecting curve used in computer graphics and animation—curves derived from the set of easing functions (Penner, 2002, Izdebski and Sawicki, 2016). This means that to describe the changes in the values of color coordinates, the appropriate (smooth) function should be used—for a “smooth start and smooth stop.” The simplest functions that produce good results are the polynomial functions of InOutQuad and InOutCubic or non-polynomial InOutSin from the set of easing functions (Penner, 2002, Izdebski and Sawicki, 2016) — Figure 2.

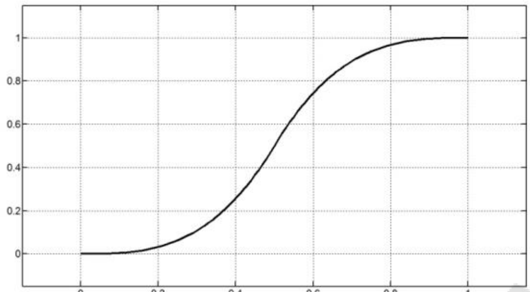

Figure 2: The InOutCubic easing function — an example of function with a “smooth start and smooth stop” (Izdebski and Sawicki, 2016).

6 THE RESULTS: CORRECTION PROCEDURE

Analysis of the results obtained from the conducted experiments allows proposing a simple procedure for color correction for stitching images in Semi-Cave. Correction is carried out independently for *R*, *G*, and *B*, assuming that in the case of each component, the other two components are zero. This procedure is based on a comparison of luminance in specific fields of adjacent (stitched) images and is carried out in the following three steps:

S1. Measure the luminance of neighboring (adjacent) fields (Figure 3).

S2. If the measured luminances have the same value, finish the correction and stop the procedure; if not, perform operation S3.

S3. In the correction program, change the displayed color—by inserting the value of an appropriate correction factor in the color coordinate. Most often, it is enough to change the value of the factor in only one of the neighboring fields, but if the differences are large, change the correction factors in both the fields, and return to S1.

The measurements carried out confirmed the possibility of using approximate formulas in versions (5) and (6) in real conditions of Semi-Cave. Therefore, it is possible to propose a simple method for determining the value of correction factors in the proposed procedure of color correction.

Figure 3: The image generated by the correction program, for example, for color *G* (0,255,0). Correction will take place along the left or right edge—where identical images will be displayed. The colors of the neighboring images are compared along the joining edge in three fields: upper, lower, and middle. The middle field corresponds to the height of the “horizon” of the displayed image. It was assumed that at such a height, the displayed information is the most important.

Let $L1_k$ be the value of the measured luminance in the first field (e.g., the image on the left side of the joining edge), where *k* is one of the components (*R*, *G*, or *B*) or corresponds to the correction of gray levels (BW—in this case, all three components are corrected equally in the program). For example, $L1_R$ is the measured luminance of the red component and corresponds to R_L in equations (1)–(6). Similarly, let $L2_k$ be the value of the measured luminance in the second field (e.g., the image on the right side of the joining edge). Let us assume that the correction factor *W* for the first field will be introduced in the color correction program. This means that $L2_k$ should be the expected luminance value after correction in the first field. Taking into account equation (5), the value of *W* can be determined on the basis of equation (7).

$$W = \frac{(L2_k)^{1/2.2}}{(L1_k)^{1/2.2}} = \left(\frac{L2_k}{L1_k}\right)^{1/2.2} \tag{7}$$

For small differences in luminance values (a maximum difference of 20%–30%—which practically always occurs in Semi-Cave), equation (7) can be represented in a simple approximated form (8) using the power series expansion.

$$W \approx 1 + 0.42 \cdot \frac{L2_k - L1_k}{L1_k} \tag{8}$$

The simple correction procedure with feedback proposed above requires consideration of specific cases. The full procedure is as follows:

P1. Check if the display geometry is correct. If not, perform the geometry correction. Select the two stitched images for color correction (called in the procedure as the left image and the right image).

P2. Carry out the correction independently for the components *R*, *G* and *B*. Repeat the procedure independently for the appropriate components. The order is not important.

P2.1. Select a component (*R* or *G* or *B*).

P2.2. Specify the level of color (binary) displayed on the control screen. As a standard, the color at the level of *R* (127,0,0) or *G* (0,127,0) or *B* (0,0,127) will be displayed. In this way, the luminance of the displayed information corresponds to approximately 18% of the full range of luminance, which is good enough for assessing the lighting in typical scenes

P2.3. Display the same control image with the specified color and specified level on both stitched images.

P2.4. Measure the luminance in the adjacent fields on both sides of the joining edge (on the left and right stitched image independently). Compare the results of the measurement.

P2.5. Apply display correction (correction factor) according to formula (8). If the difference in luminance of measurements between images (left and right) is small, apply correction only for one image (either left or right). If the difference is greater (above 15%), apply the correction for both images.

P2.6. Repeat the luminance measurement. If the difference is aligned, finish the correction for a given pair of fields (or for a given component), if there are still measurable differences, repeat operations P2.4 – P2.5.

P3. Display both the images in a standard view (such that the entire surface of the image is visible, not just the separate squares). Rate visually the stitched images. Evaluate the adjacent fields at different heights of the joining edges. If still there are perceptual or measurement differences, repeat the whole P2 operation of correction procedure.

On the basis of the procedure proposed for color correction, an application carrying out appropriate tasks has been prepared. The software has been implemented in Visual Studio using the Vulkan libraries (Sellers and Kessenich, 2016) and OpenGL (Sellers et al., 2015), and works on the level of shader drivers (Bailey and Cunningham, 2011). The application works in two modes: edit mode and work mode. Both modes use a common code associated with managing the display of windows in a Windows environment.

Operations of color correction were combined with previously developed program for geometric correction (Sawicki et al., 2018), thereby creating one subsystem for display correction.

7 VERIFICATION OF THE SOLUTION

The method developed for color correction was tested using selected color images. The tests verified the color composition between the images, which had different degrees of complexity and showed color variations. The comparison was based both on perceptual verification and on the luminance measurements obtained for each component.

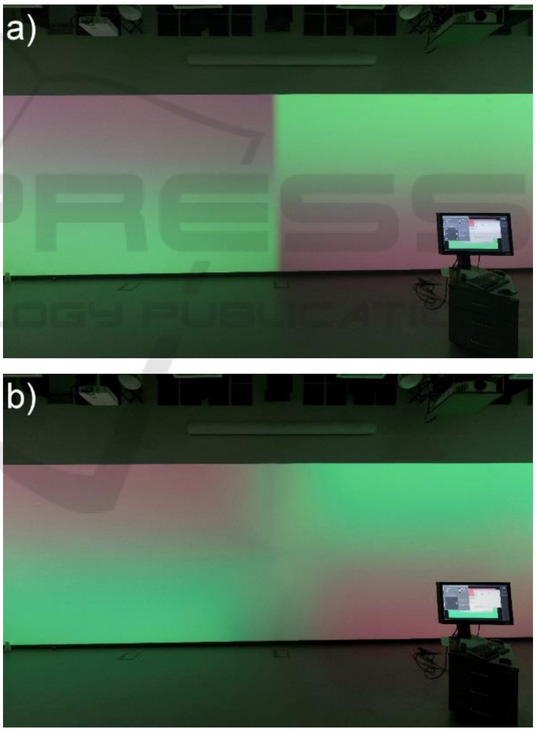

Figure 4: An example of stitching two images with a large color mismatch between components. The images were combined with up-down and down-up changes between *R* and *G*: from (255,127,127) to (127,255,127). a) Stitched images before correction. b) After correction.

Preliminary stitching tests carried out with the images with color correction within each color component showed positive results. The stitching tests were further carried out with specially prepared images that had very large color mismatches both within one component and between two components. An example of image correction is presented in Figure 4. The stitching tests were carried out to confirm the correctness of the operation of the developed correction system. Changes in the correction level (or changes in the values of correction factors) are subject to linear dependencies. The correction problem is scalable – can be scaled to the range allowed by the maximum hardware settings. Therefore, if it is possible to achieve adequate correction for selected (very large) color differences, it will also be possible to achieve proper correction for all smaller color differences

Figure 5: An example view of the presented VR environment generated in Semi-Cave. The photo was taken from a point consistent with the position of the observer in VR.

To check the operation of the entire subsystem developed for the correction of both geometry and color in Semi-Cave, we used UNITY to create a VR environment. The principles of perspective projection for acquiring images were determined, taking into account the size and shape of the laboratory. It was assumed that the observer (projection center) is located exactly in the center of the room. Images created using the methods of computer graphics allow defining elements with an accuracy of 1 pixel. In addition, computer graphics facilitate changing the projection conditions and display conditions. This approach allows visual evaluation of the correctness of the display. In our case, visual evaluation is considered the best because it gives an opportunity to evaluate the perception of images and immersion into a VR environment. We carried out the evaluation with 10 participants (other than authors). The conducted tests confirmed the correctness of the operation of the display system. A sample picture taken in Semi-Cave, using Sponza Palace in Dubrovnik as a model to create a VR, is shown in Figure 5.

8 SUMMARY

Image stitching in the Semi-Cave installation is a complex issue involving several independent problems. The subsystem developed for the correction of geometry and color is an individual solution adapted to the conditions of Semi-Cave. In addition, our software used for display driver allows for full control of the entire process of displaying information.

Color correction is a much more difficult task than geometry correction. It requires obtaining a series of measurements under strictly defined conditions. In addition, it requires the use of a specially prepared set of control images. Therefore, the solution developed both indicates the specific methods for conducting correction and helps prepare the environment to carry out this correction.

The analysis of the process of displaying information in real conditions of Semi-Cave showed that the best solution would be to perform an indirect comparison of colors displayed in the neighboring images. For this, control images with colors corresponding to a particular *R*, *G*, *B* component were used, and the luminance measurement was carried out. The measurement obtained helped in carrying out the color correction in a convenient way.

The tests carried out showed that the developed method allows achieving seamless stitching of images in terms of their color matching. The method can give good results even if an extreme color mismatch existed before correction. The entire subsystem (for the correction of geometry and color) was also tested using the VR environment created for Semi-Cave. It was assumed that the observer's location and perspective projection (in the VR) were consistent with the shape and size of the real room. The best test in this situation is the perceptual assessment and the impression of immersion into the VR. The experiments carried out confirmed the correctness of the operation of the developed system.

It is worth comparing our method to solutions known from the literature. The installation conditions of Semi-Cave allowed performing the geometry correction independently as the first step. In this way, we could assume that the images are already geometrically corrected—this means that it has simplified the task in relation to advanced contemporary methods (Bellavia and Colombo, 2018). On the other hand, the task turned out to be much more difficult because of the need to measure the luminance/color (and its components)—a problem that does not occur with the typical stitching of the panorama (Bellavia and Colombo, 2018).

The original method of seamless stitching of images in the Semi-Cave installation is presented in this paper. However, we only consider it as a technical tool necessary to create a convincing VR environment for conducting scientific research in the future. We are planning to create a VR environment which will help reproduce images of workplaces, garden, forest, etc. This will allow examining the impact of the visual environment (objects, colors, contrasts, etc.) on the cognitive performance and the well-being of the subjects.

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