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RGB Color Model: Effect of Color Change on a User in the VR Art Gallery Using Polygraph

Irena Drofova [1,*], Paul Richard [2,*], Martin Fajkus [1], Pavel Valasek [1], Stanislav Sehnalek [1] and Milan Adamek [1]

[1] Faculty of Applied Informatics; Tomas Bata University in Zlin; Czech Republic
[2] Polytech Angers, University of Angers, Angers, France
* Correspondence: drofova@utb.cz (I.D.); paul.richard@univ-angers.fr (P.R.)

Abstract: This paper presents computer and color vision research focusing on human color perception in VR environments. A VR art gallery with digital twins of original artworks is created for this experiment. In this research, the field of colorimetry and the application of CMYK and RGB color models are applied. The interrelationships of the two colors models are applied to create a color modification of the VR art gallery environment using C# Script procedures. This color-edited VR environment works with a smooth change of color tone in a given time interval. At the same time, a sudden change in the color of the RGB environment is defined in this interval. This experiment aims to record a user's reaction embedded in a VR environment and the effect of color changes on human perception in a VR environment. The research uses lie detector sensors that record the physiological changes of the user embedded in VR. Five sensors are used to record the signal. An experiment on the influence of the user's color perception in a VR environment using lie detector sensors has never been conducted. This research defines the basic methodology for analyzing and evaluating the recorded signals from the lie detector. The presented text thus provides a basis for further research in the field of colors and human color vision in a VR environment and lays an objective basis for use in many scientific and commercial areas.

Keywords: color model; art gallery; virtual reality; art digitization; digital twins; artwork; 3D model; lie detector; polygraph; sensors; signals

1. Introduction

This document presents research on color vision in a virtual reality (VR) environment. Currently, color vision, as well as computer graphics and computer vision, is an integral part of information technology issues. We encounter computer graphics in almost all fields. At the same time, Computer graphics and Image processing use differ in each field and individual subdisciplines. With 3D graphics and three-dimensional space development, new approaches and solutions have emerged in this field. The basic principles of 2D graphics and analog technologies are smoothly reflected in digital 3D image processing. [1] Awareness of these procedures makes it easier to work with images, colors, or materials so that they fully correspond to the perception of the environment by the human eye. [2] All these principles are used today in the game industry, engineering, design, architecture, art, therapy, military, criminology, agriculture, psychology, chemistry, and other fields. [3–5]

Currently, environments are usually created and simulated in 3D space, virtual, or augmented reality. [6] For the human eye to perceive virtual objects, scenes, and environments realistically, the science of colors, color models, color spaces, light radiation, the anatomy of the human eye, and *Human vision* is fully applied. [7] These issues are summarized and described in more detail by the *Colorimetry* and *Color management* field. It is a vast field of science. *Colorimetry* includes color calibration of display devices, issues of printing, light, sensing devices, analog and digital processing of image data and signals, color mixing, digital description of colors, tone, color psychology, and

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more. [7,8] The issue of *Colorimetry* and *Color vision* is currently the subject of extensive research in many scientific fields.

This manuscript describes the basic principles of mixing primary and secondary colors. These basic principles are experimentally applied in a virtual reality (VR) environment to observe the influence of colors and color changes on human color perception. The display and perception of colors in a VR environment have already been the subject of some research. [9] However, the experiment described in this paper has not yet been performed. For these purposes, an art gallery was created in a virtual environment. In this virtual reality environment, real works of art by the painter Michal Pasma, which have been digitized, are presented. The experiment aims to capture the color changes of a user embedded in a virtual gallery environment. A lie detector was used to identify changes in color perception in the environment. Several scientific research experiments have already been conducted with this device as well. Mainly in the field of human psychology and perception. [10–12]

This experiment explores the possibilities of working with color vision and the **RGB** (Red, Green, Blue) color model in a VR environment. This experiment can be the basis for further research in the field of *Computer vision, Color vision*, and the effect of the environment on the user embedded in VR. The practical use is possible in medicine, psychology, therapies, or educational programs, as well as in commercial fields. It is not known that a similar experiment has already been implemented and the issue of color vision applied in a VR environment using a lie detector for data analysis.

2. Digital Twins of the Artworks

A digitized image of actual works of art is used in this study. The art paintings were photographed with a *Pentax K-50 DSLR camera*. The image was taken in an art gallery room without artificial lighting. The room was lit by natural daylight. The captured digital image was edited in the 2D software *Camera RAW 14.5* for photo editing. The digital image was edited with brightness, contrast, and exposure functions and then trimmed to the final display. Twelve artworks and one information panel about the exhibition's author were imported into the virtual art gallery. Figure 1 shows the reference artwork a) in the first capture step and b) the digitized and post-production edited artwork for application in the VR gallery environment.

(**a**) (**b**)

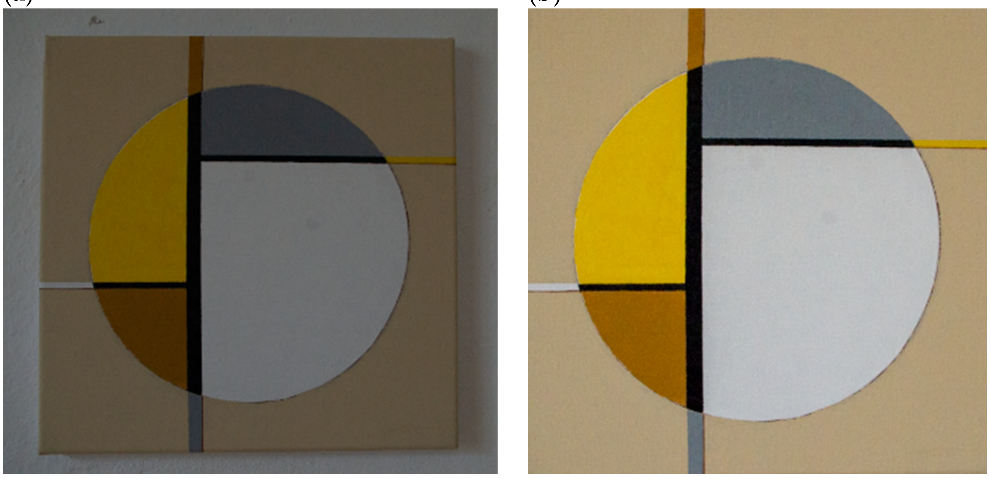

Figure 1. Digitization and creation of a digital twin of a work of art: a) an original image in an art gallery environment and b) a digitized art image for a VR environment.

The digital image editing procedure is not the subject of this experimental study. The works of art serve primarily as objects intended to focus the user's attention embedded in the created VR environment. The **RGB** color model was used as part of digital imaging in this image processing.

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3. Color Model RGB and CMYK

Digital display devices use the **RGB** (Red/Green/Blue) color model. [13] The **CMYK** (Cyan/Magenta/Yellow/Contrast) color model in turn represents the process of transferring colors to the material. [14] Therefore, it is necessary to recalculate these color models. Compared to other research studies, this experiment performs the necessary recalculation of both mentioned color models. [15,16] Searching for a complex solution for the transformation of color models was unnecessary in this case. In this study, the primary colors of the **CMYK** color model are supplemented in the display device. [17] **RGB** and **CMYK** color models are shown in Figure 2.

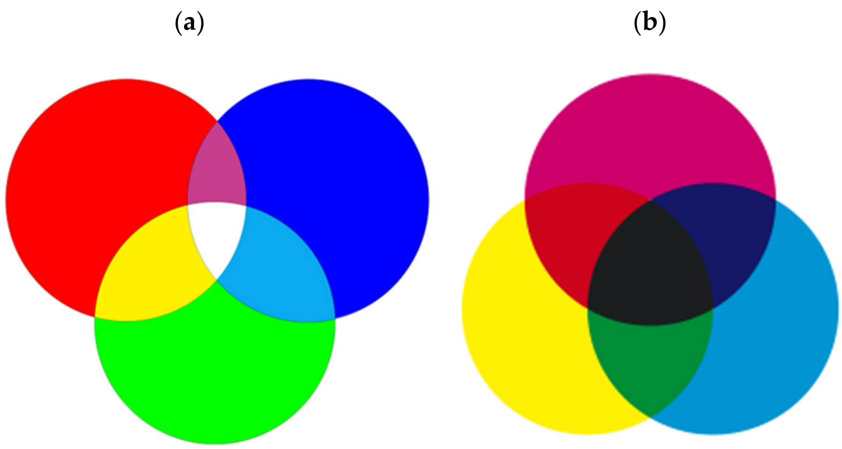

Figure 2. Color Models: a) RGB color model and b) CMYK color model. [16].

The **RGB** color model has values **0-255**. The **CMYK** color model is presented in the **0** and **1** systems. It is necessary to convert their values to work with the mentioned color models. **CMYK** values must be changed from the **0.1** range to the range **0-255**. In order to be able to define colors in this way, it is necessary to convert the **RGB** colors from the **0-255** range to the **0.1** range in the first step:

$$R' = R/255 \tag{1}$$

$$G' = G/255 \tag{2}$$

$$B' = B/255 \tag{3}$$

The Contrast color (K) is calculated from Red (R'), Green (G'), and Blue (B'):

$$K = 1 - max\ (R', G', B') \tag{4}$$

Formulas for converting CMY color values to RGB color model values:

$$C = (1 - R' - K)\ /\ (1 - K) \tag{5}$$

$$M = (1 - G' - K)\ /\ (1 - K) \tag{6}$$

$$Y = (1 - B' - K)\ /\ (1 - K) \tag{7}$$

The following Table 1 shows the conversions of **RGB** and **CMYK** color values.

Table 1. CMYK and RGB Absolut Color Value.

COLOR	CMYK VALUE	RGB VALUE
R	(0,1,1,0)	(255,0,0)
G	(1,0,1,0)	(0,255,0)
B	(1,1,0,0)	(0,0,255)

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C	(1,0,0,0)	(0,255,255)
M	(0,1,0,0)	(255,0,255)
Y	(0,0,1,0)	(255,255,0)
K	(0,0,0,1)	(0,0,0)
W[1]	(0,0,0,0)	(255,255,255)

[1]RGB color model also works with white (W) with white light, which is created by mixing all three absolute values of the color components of light R, G, B.

As mentioned above, the basic principles of working with **RGB** and **CMYK** color models and the basic definition of absolute color values in both models were applied in this research. The experiment also uses the value of white light, which is created when all three absolute **RGB** colors are used. It is given as [1]**W** in Table 1. This absolute value of [1]**W (255,255,255)** is also the starting point for a practical experiment with colors in the virtual environment of an art gallery. The following section is a description of creating a virtual art gallery environment. The study focuses on the changing color environment and the user's perception of these changes embedded in a VR art gallery environment. In this environment, converted color values to an **RGB** color model are used.

4. The Virtual Art Gallery

In the software for creating 3D objects and VR environment *Unity engine (2021)*, a room is created in a virtual environment for the experiment's needs. [18] Realistic art objects by the Czech artist Martin Pasma were presented in this virtual gallery. As Figure 3 shows, the walls of the virtual room have a default color of **W** (White), which has a value of **(255,255,255)** in the **RGB** color model. The color values of the virtual room's walls change during the user's embedding into the VR environment, as well as its tone. The essence of the color modification of the environment is (among other things) to record to what extent and when the user notices a change in the virtual environment. The artistic images presented in the virtual art gallery were crucial in directing and maintaining the user's immediate attention in the created environment. The user could actively move and study the details of the images up close or from any distance as a complete unit of the presented topic.

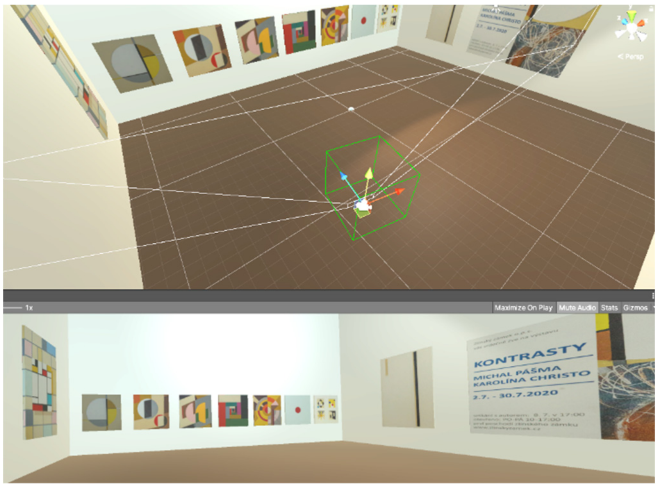

Figure 3. The virtual art gallery environment.

The white color of the room's walls, which highlighted the presented images, was static in the first minute after starting and embedding the user into the VR. After that, the walls began smoothly changing the color value to another tone and color. A range of pre-defined colors was used. Figure 4 shows the VR environment and its reference color modifications.

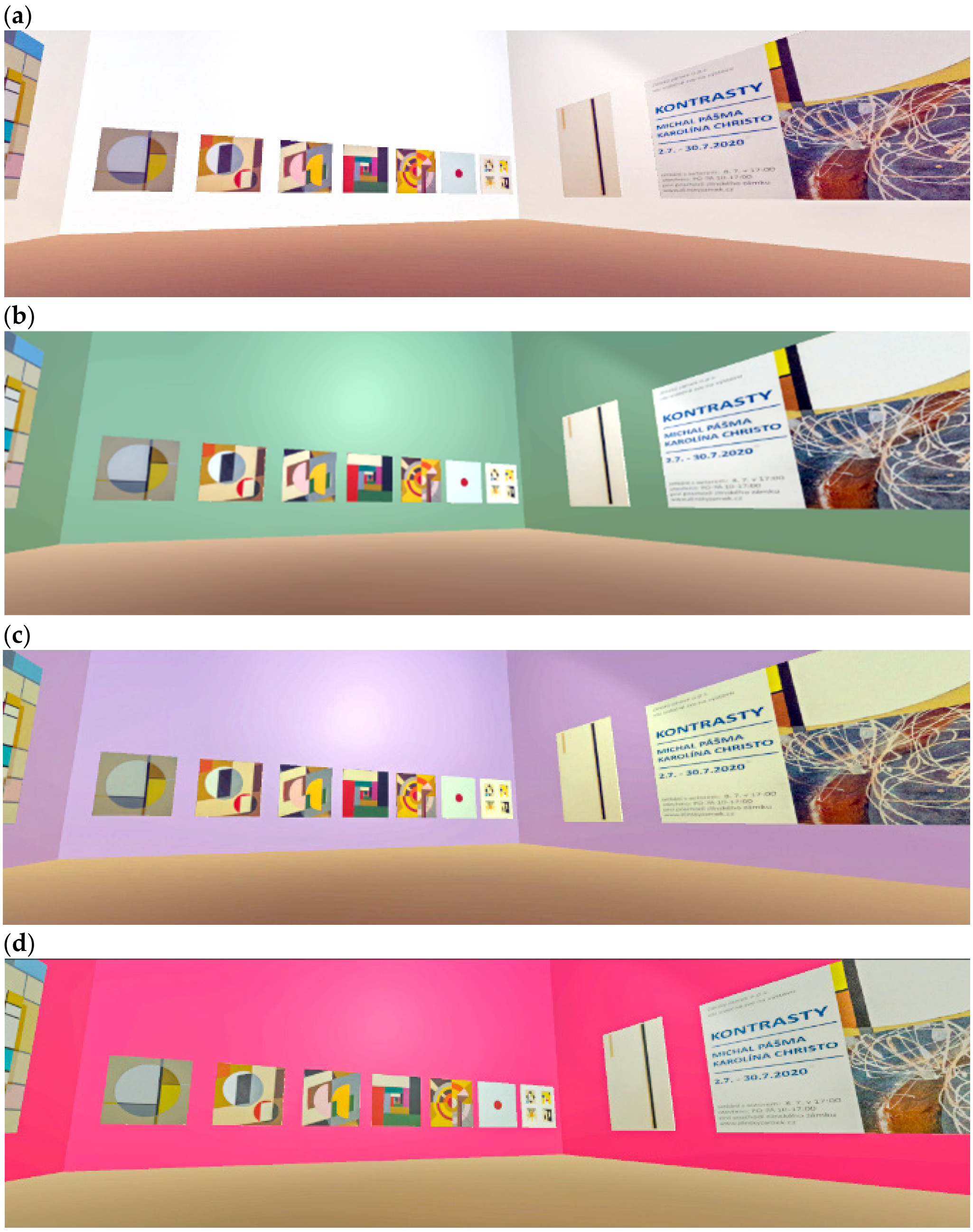

Figure 4. The initial white background of the VR environment, b), c), d) reference images of the smooth color tone change of the VR gallery environment.

In individual steps indistinguishable from the human eye, these color changes took place over 15 minutes until the first input value of the wall color **W** (White), and then the cycle was repeated. However, three sudden intervals with a very contrasting change in the color of the environment were also defined during the cycle. The absolute values of the color model **R (255), G (255),** and **B (255)** were chosen to measure their influence on the user's physiological changes in VR. These colors were defined in the environment statically for 10 seconds. Figure 5 shows the VR environment in **R, G,** and **B background** color intervals.

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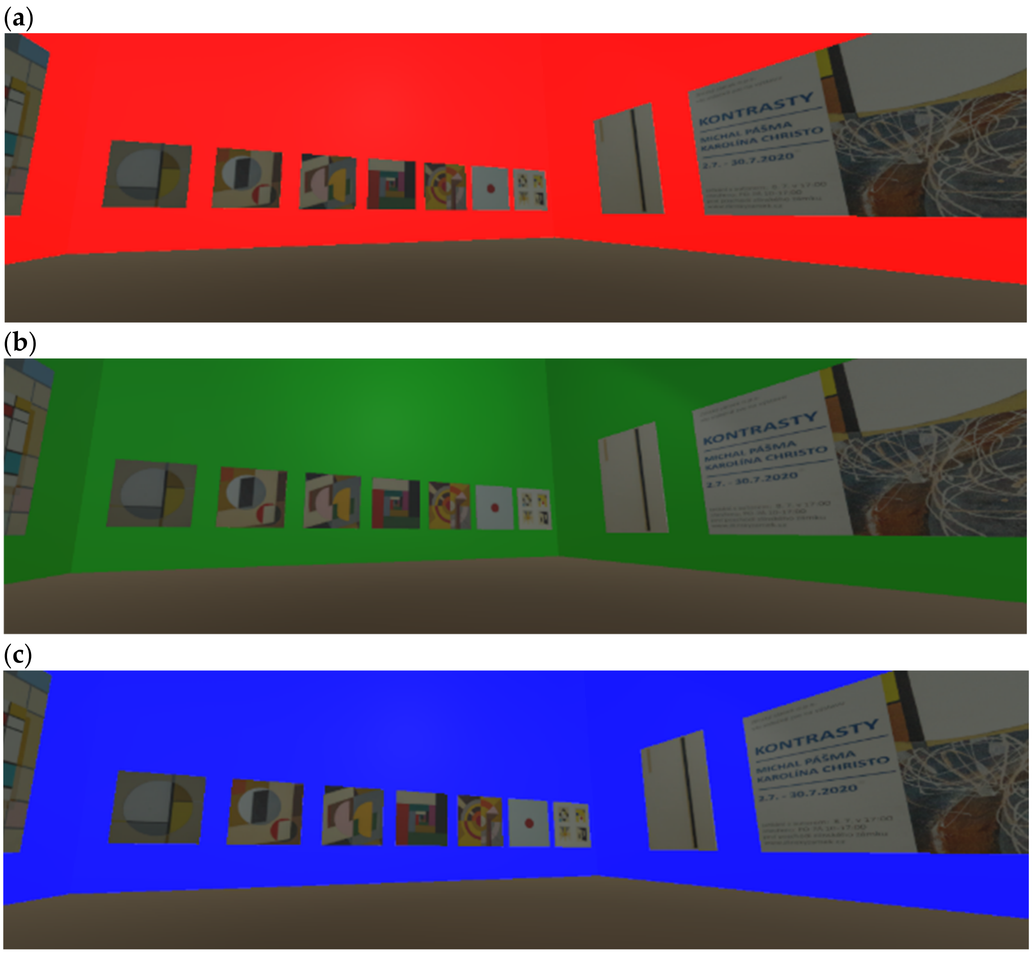

Figure 5. Static direct absolute RGB process colors: a) direct absolute background color R(255), b) direct absolute background color G(255), c), direct absolute background color B(255).

As it was written in this text, the virtual environment of the gallery was created with a color-modifiable background. These color modifications were applied to the walls of the room in the VR environment. The starting background color was **W** (White), which varied smoothly by one tone across the entire color gamut in a 15-min time cycle. Into this cycle, step-by-step changes to the absolute colors of the **RGB** color model were applied. These change color modifications aimed to observe the user's physiological changes embedded in the VR environment. The lie detector recorded these changes. The following section describes applying color changes in the VR gallery.

5. C# Script Color Modification

One of the ways to achieve a smooth transition of an object's color to another color in the Unity engine is by using a C# script. Within the script, we can choose the object, its exact color, and the conditions under which this color will change. This project uses such a script for smooth transitions between 7 different colors. Initially, the desired colors are selected and written in 3 sheets, each containing one of the color components **RGB** (red, green, blue) in the same order in which the colors will be displayed and gradually modified:

```
public int[] colR = { 0, 255, 147, 221, 255, 106, 255 };

public int[] colG = { 255, 0, 112, 160, 0, 90, 255};

public int[] colB = { 0, 255, 219, 221, 0, 205, 255};
```

Also need to specify 3 other colors:

1. The color that will change ("actualColor" variable).
2. The color will change to (variables "activeR", "activeG", "activeB").

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3. The current color of the object (variables "nextR", "nextG", nextB").

First, using the "**activeColor**" variable from the sheets with color values, we call up the value of the color from which we want to start the modification. We save the individual color components in the variables "activeR", "activeG", "activeB":

```
activeR = colR[actualColor];

activeG = colG[actualColor];

activeB = colB[actualColor];
```

The color parameters of the next transition are obtained in a similar way. Next add 1 to the variable "**actualColor**", and the parameters of the following colors are obtained from the lists of color folders. These colors are stored in the variables "**nextR**", "**nextG**" **and** "**nextB**":

```
nextR = colR[actualColor+1];

nextG = colG[actualColor+1];

nextB = colB[actualColor+1];
```

In the next steps, the individual "active**X**" variables are used to store the transition color parameters. The values of these variables are then numerically approximated to the "next**X**" values. A value of **1** is chosen for one step of color approximation.

For each color component, a special method is used which it is decided:

1. Whether it is necessary to add or subtract one step to "approach" the next color.
2. Whether the given parameter has already reached the required value.

```
void calculateR()

{

int split = activeR - nextR;

if (div > 0) { activeR = activeR - 1; doneR = false; }

if (div < 0) { activeR = activeR + 1; doneR = false; }

if (div == 0) { doneR = true; }

tempR = (float)sctiveR / 255;

}
```

Two more variables are also assigned to each color component:

- done**X**
    - Variable of type **Boolean**.
    - Contains information whether the given color component has already reached the required value. In case the color folder variables "active**X**" and "other**X**" contain the same values, this variable is set to "true", otherwise it remains "false".
- temp**X**
    - variable of type **float**
    - is used to convert integer variable values to **integer** variables.

In general, it is customary to use whole numbers in the range **0-255** to express individual color components, however, in the *Unity engine*, a decimal number with an interval of **0-1** is used for individual color components. Based on the logical continuity of the individual operations, a procedure was chosen where the individual colors between which we want to create a transition are entered in the usual values and the recalculation is only carried out within the running of the script.

Scripts used within the *Unity engine*, by their very nature, allow certain steps to be performed for each newly displayed image on the screen in the form of the "**Update ()**" method. The commands written in this method are then directly dependent on the number of frames per second (FPS). As part of the chosen procedure for modifying the color of objects, it is also necessary to determine at

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what speed the color transition will take place between individual colors and their color components. In this case, two numeric variables "**counter**" and "**interval**" were chosen:

- Counter
    - Variable, tracking the order of the current frame.
- Interval
    - Determines how many times the scene is rendered as individual frames before the color components are recalculated and the color of the selected object is updated.

Every time, when the "**Update()**" function is selected, the value of the "counter" variable is increased by 1. If the "**contour**" variable reaches the value of the "**interval**" variable, the new values are set in the "temp**X**" variables, these are applied to the requested object, and the value of the "interval" variable is set to **0** again.

```
if (counour == interval) { recountR(); recalculateG(); recalculateB();

zed.GetComponent<Renderer>().material.color = new Color(tempR, tempG, tempB); counter = 0; }
```

Achieving the desired color is detected using the "done**X**" variables. Suppose these variables for all color components contain the value "**true**" it follows from the logical context that all color components have already reached the values of the color to which the original color was changed, and all variables can be set to values corresponding to the transition to the next color from the list. Otherwise, it is necessary to repeat the individual steps of the selected procedure until the mentioned condition is met.

```
if (doneR && doneG && doneB) {

actualColor++;

nextR = colR[actualColor + 1];

nextG = colG[actualColor + 1];

nextB = colB[actualColor + 1];

doneR = false;

doneG = false;

doneB = false;

}
```

6. C# Polygraph Sensor and Signals

The user's reaction is embedded in the VR gallery environment. A model situation is created using lie detector sensors (polygraph). Lie detectors are currently used in many fields, especially criminology, law, and psychology. At the same time, they are also the subject of unmeasured data analysis and evaluation. [19–24] It is usually a measurement of changes in physiological properties induced by a specific stimulus. However, an experiment measuring the effect of background color changes on a user embedded in a VR environment has not yet been carried out. Regarding *Human color vision*, it can be assumed that a sudden change in the color of the virtual environment will be a stimulus for a change in physiological properties. The lie detector LX6 from the *Lafayette Instrument POLYGRAPH* company was chosen for these purposes. [25] Figure 6 shows a user embedded in a VR environment and connected to sensors to measure changes in physiological properties using a lie detector.

Figure 6 shows a user nested in a gallery in a virtual reality environment. The numbers 1 and 3 in Figure 6 define the computing devices used in this experiment. *Rectangle* number 2 shows a device mediating the user's visual immersion in a virtual art gallery using the Oculus Quest2 VR headset. The user embedded in the VR environment is simultaneously connected to the sensors of the polygraph. Sensors for measuring physiological changes are marked in Figure 6 in *rectangles* 4-7: [26,27]

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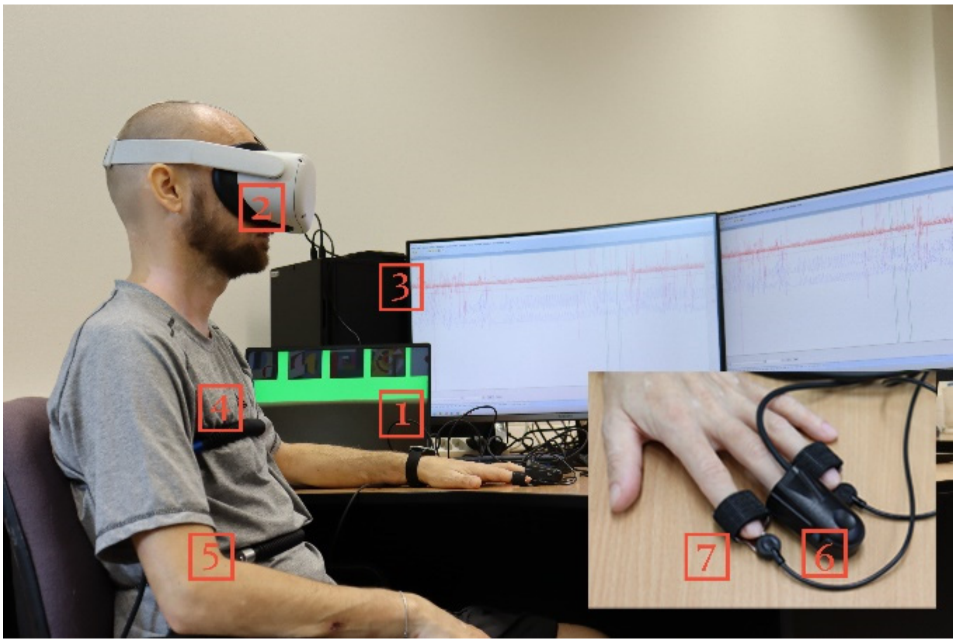

Figure 6. User captured by lie detector sensors in a virtual gallery environment: 1) and 3) computing and display units, 2) VR Headset, 4) and 5) Pneumo Chest Assembly, 6), Photoelectric Plethysmograph 7) Electrodermal Activity (EDA).

6.1. Pneumograph (Sensors 4 a 5)

Two sensors are attached to the user's body, measuring breathing in the chest and abdominal area. During breathing, the air is exchanged during inhalation and exhalation. Regular breathing can be defined by its frequency. This frequency can be determined by the number of breaths per minute. These are respiratory sensors, which are indicated by frames 4 and 5. Sensor 4 detects the frequency of breathing in the area of the upper respiratory tract, and sensor 5 in the vicinity of the diaphragm. These sensors have the task of monitoring changes in lung volume, breathing intensity, and breathing rhythm. The standard breathing rate for healthy adults is 16-20 breaths per minute. Analyzing data from pneumograph sensors is challenging. The user can arbitrarily change the frequency of the breath. Another factor influencing the resulting data can be natural factors, such as coughing, sneezing, swallowing, or talking.

6.2. Photoelectric Plethysmograph (Sensor 6)

This sensor records rapid changes in pulse blood volume. The sensor records the change through a photosensitive sensor that measures the light reflected or transmitted through the skin. The intensity of the red light falling on the sensor is directly related to the amount of blood. The sensor is, therefore, a blood flow sensor and is shown in Figure 6 in box number 6. It is sometimes referred to as relative blood pressure (RBP), which is what is called "cardiovascular" or "relative blood volume." RBPs are shown in the waveforms as two types of signals, blood pressure and pulse change. It is therefore a capture of the amplitude in the duration of the change in blood pressure and the change in pulse waves.

6.3. Electrodermal Activity EDA (Sensor 7)

The galvanic skin response (GSR) sensor records a change in the skin's ability to conduct electricity, where skin conductivity is a prerequisite, and its change is a sign of excitement, nervousness, or psychological pressure. Skin conductance is measured using two stainless steel fingertip electrodes, and sweat gland activity is recorded. In this experiment, the change in skin resistance is measured based on sweat gland activity.

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6.3. Activity Sensor

This sensor is not shown in Figure 6. It is a pressure and movement sensor. The sensor is a chair pad that captures the movement of a seated user embedded in VR. This sensor can also be used on the hands or feet. Figure 7 shows a reference recording of signals from individual sensors, which are listed under the following designation:

- P1 Abdominal Respiration trace;
- P2 Thoracic Respiration trace;
- PL Photoelectric Plethysmograph;
- SE Activity Sensor;
- GS Electrodermal Activity (EDA).

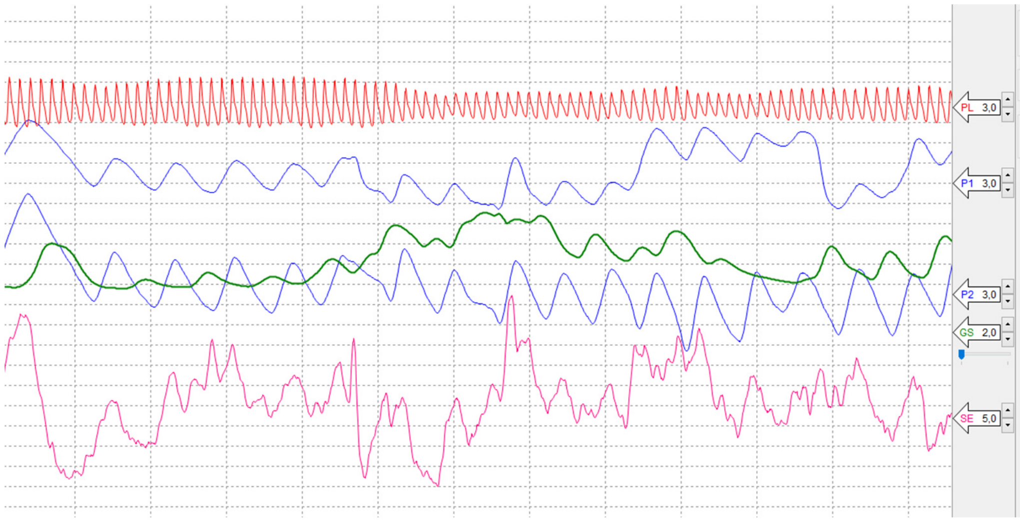

Figure 7. User captured by lie detector sensors in a virtual gallery environment: 1) and 3) computing and display units, 2) VR Headset, 4) and 5) Pneumo Chest Assembly, 6), Photoelectric Plethysmograph 7) Electrodermal Activity (EDA).

Signals from lie detector sensors and their data are processed by software (SW) *Lafayette Polygraph System 11.8.5*. The processing of signals from all mentioned sensors and the analysis of the measured output data from the lie detector is described in more detail in the following chapter.

7. Results

There are many options for evaluating the measured data from the lie detector. The output measured data can be interpreted numerically and also with a graph. The methods used always depend on the purpose and goal of using the lie detector. [26–30] In this experiment, a polygraph (lie detector) was used to record the physiological changes of a user embedded in a VR environment. Changing the colors of the VR environment was supposed to cause these physiological changes in the user. That involved a sudden change in color at a given interval when the user was embedded in a changing environment of a virtual art gallery. The measurement was carried out to detect physiological changes of the user to the reaction of three absolute process colors **RGB** in the VR environment. Thus, the values of these **R(255)G(255)B(255)** absolute colors formed a sudden color change in the background of the virtual gallery.

Recall that the RGB color model does not work with physical color but with colored light. That is how colors are applied in digital environments, devices, or digital output devices. There were using the principles of color and human vision. These changes were recorded using lie detector sensors, which are described in more detail in the previous chapter. Figure 8 shows the entire time interval of the user's immersion in the VR gallery environment and the lie detector connected to the sensors. It is not known that a similar experiment has been conducted in the area of color and human vision in

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a VR environment. It was, therefore, not clear in advance whether the sensor detectors would detect the user's physiological changes. There are also no studies to back this experiment up.

Figure 8 shows the total recording of signals from all mentioned sensors in a time interval of 18 minutes. During this time, the user was embedded in the virtual gallery environment and connected to the sensors of the individual sensors.

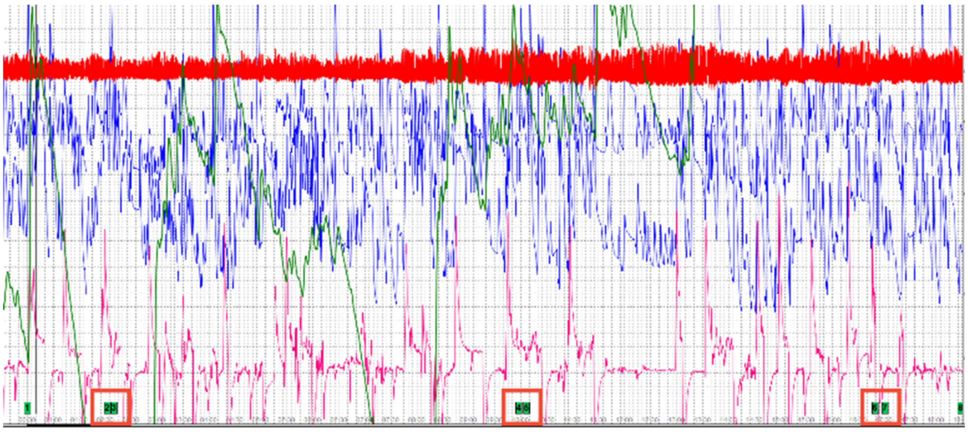

Figure 8. Display of lie detector signals measured by sensors in the total measurement time interval.

As shown in Figure 8, it is a recording of the signal of all the mentioned sensors in a time interval of 18 minutes. The red squares in the lower part of the measured data indicate the time intervals of the step change of the background color to absolute colors. The output of the sensor measurement was a large amount of measured data from all the listed sensors. This data was generated at an **interval of 0.03 seconds**. Therefore, the output data had to be analyzed and simplified. For each type of sensor in the total measurement time, the following was determined:

Total minimum value $^{a}T_{min}$ | Total maximum value $^{b}T_{max}$

These upper and lower bounds of the output recorded data were then defined in the interval of each absolute **RGB** color, which represented the sudden change of the color environment for 10 seconds in the VR art gallery in the following order:

G(255) G_{min} | G_{max} ; R(255) R_{min} | R_{max} ; B(255) B_{min} | B_{max}

The following Table 2 lists all the minimum and maximum values obtained from the total amount of measured data. Table 2 also lists the individual sensors according to their designation in the *SW Lafayette Polygraph System*, as described in Figure 7. Individual sensors are represented by the following labels: **P1** Abdominal Respiration trace; **P2** Thoracic Respiration trace; **PL** Photoelectric Plethysmograph; **SE** Activity Sensor; **GS** Electrodermal Activity (EDA).

Table 2. Polygraph Sensors Signal Values.

COLOR	POLYGRAPH SENSORS				
	P2	P1	PL	SE	GS
$^{a}T_{min}$	1 373 308 581	1 356 380 146	878 852 659	435 142 537	3 674 121
$^{b}T_{max}$	1 700 740 365	1 689 799 170	1 409 655 943	932 446 398	3 781 921
G_{min}	1 544 195 568	1 480 290 055	1 007 992 714	693 660 008	3 681 374
G_{max}	1 700 740 365	1 687 747 380	1 278 472 078	765 109 824	3 684 355
R_{min}	1 530 578 442	1 484 640 044	942 374 819	711 869 260	3 729 730

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R_{max}	1 661 776 075	1 643 523 274	1 336 146 189	730 070 195	3 733 444
B_{min}	1 453 597 565	1 467 732 400	934 089 157	438 385 740	3 753 788
B_{max}	1 618 014 160	1 610 575 557	1 273 883 604	741 224 476	3 779 356

The following graphic processing in Figure 9 shows this evaluated data for each of the individual colors compared with the minimum and maximum values from the total volume of data.

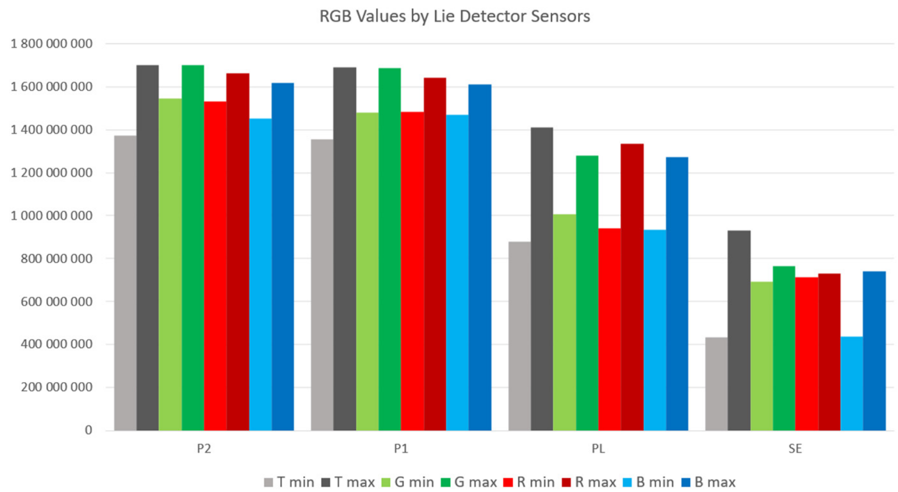

Figure 9. Graphic representation of signals measured by polygraph sensors.

Figure 9 shows the differences in the output values of signals measured by individual sensors. It can be seen from the graphic representation that the user embedded in the VR environment of the art gallery perceived a sudden change in the color of the environment. The graph shows the values of sensors **P1** Abdominal Respiration trace, **P2** Thoracic Respiration trace, **PL** Photoelectric Plethysmograph, and **SE** Activity Sensor. The graph in Figure 9 does not show the signal values from the **GS Electrodermal Activity (EDA)** sensor. According to the values shown in Table 2, it is evident that these values measured by this sensor are significantly lower. For this sensor, a statistical evaluation procedure using a statistical **"Time series method"** was used, and a *continuous linear trend* was calculated, which is shown in Figure 10 and mathematically described:

$$\textbf{GS} \quad y = 58{,}461x + 4E{+}06 \tag{8}$$

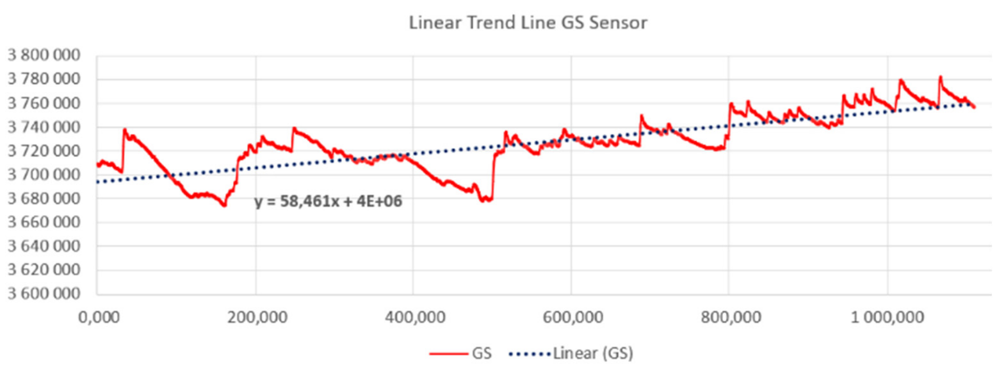

Figure 10. Graphic representation of the GS sensor signal (EDA).

From the waveform of the recorded signal from the GS sensor (EDA) and the linear function shown in Figure 10, it can be seen that a physiological change of the user embedded in the VR environment occurred in the total time interval. Table 3 shows the reaction to the individual absolute

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values of the RGB colors. The table below shows the differences in the measured values of all sensors in the individual intervals of the color change of the environment in connection with the total interval of the user's immersion in the VR environment:

$$G(255)\ G_{min}\ |\ R(255)\ R_{min}\ |\ B(255)\ B_{min}\ |\ -\ (\ {}^{a}T_{min}\ )$$
$$(\ {}^{b}T_{max}\ )\ -\ |\ G(255)\ G_{max}\ |\ R(255)\ R_{max}\ |\ B(255)\ B_{max}$$

Table 3. Differences of the Values RGB and ${}^{a}T_{min}$ | ${}^{b}T_{max}$.

COLOR	POLYGRAPH SENSORS				
	P2	P1	PL	SE	GS
${}^{a}T_{min}$	1 373 308 581	1 356 380 146	878 852 659	435 142 537	3 674 121
${}^{b}T_{max}$	1 700 740 365	1 689 799 170	1 409 655 943	932 446 398	3 781 921
G_{min}	1 544 195 568	1 480 290 055	1 007 992 714	693 660 008	3 681 374
G_{max}	1 700 740 365	1 687 747 380	1 278 472 078	765 109 824	3 684 355
R_{min}	1 530 578 442	1 484 640 044	942 374 819	711 869 260	3 729 730
R_{max}	1 661 776 075	1 643 523 274	1 336 146 189	730 070 195	3 733 444
B_{min}	1 453 597 565	1 467 732 400	934 089 157	438 385 740	3 753 788
B_{max}	1 618 014 160	1 610 575 557	1 273 883 604	741 224 476	3 779 356

Numerical values measured by all mentioned lie detector sensors show the physiological changes of the user in response to a sudden change of color in the virtual gallery environment, as shown in Table 3 and Figures 9 and 10. It is necessary to mention that other attributes affect the entire experiment during the measurement and subsequent analysis of the obtained data. That is a model situation to find out whether the sensors of the lie detector will capture the physiological changes of the user immersed in the VR art gallery. The evaluation of the measured values of the GS sensor is performed differently due to the order of magnitude lower values of the signal recorded by this sensor, as shown in Figure 10. This procedure suggests a possible further evaluation of the entire variable environment in a smooth transition of color tone between intervals of sudden RGB color changes. This issue is described in chapters 3 and 4. For further research, linear functions were determined for all other sensors used in this experiment. Figures 11 and 12 shows their graphic representation.

$$\textbf{P1} \quad y = 2075{,}7x + 1E{+}09 \tag{9}$$

$$\textbf{P2} \quad y = -44509x + 2E{+}09 \tag{10}$$

$$\textbf{PL} \quad y = 156{,}04x + 1E{+}09 \tag{11}$$

$$\textbf{SE} \quad y = -2021{,}5x + 7E{+}08 \tag{12}$$

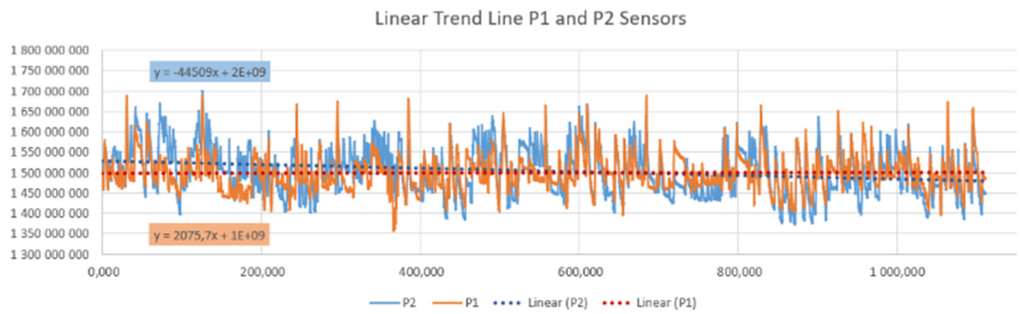

Figure 11. Graphic representation of the signal from the sensor P1 Abdominal Respiration trace and P2 Thoracic Respiration trace.

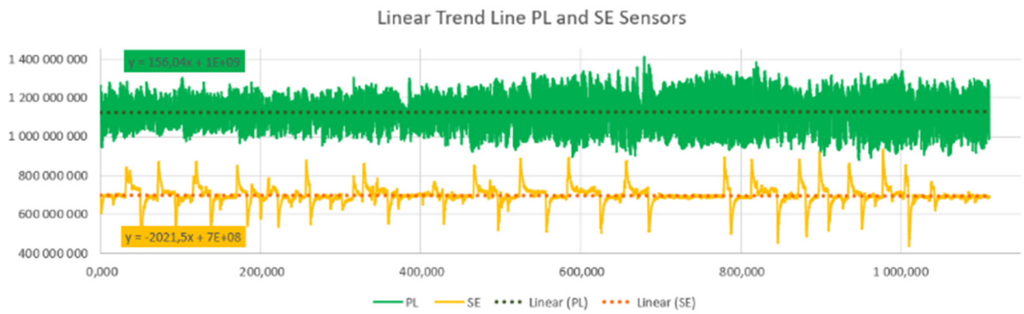

Figure 12. Graphic representation of the signal from the PL Photoelectric Plethysmograph and SE Activity Sensor sensors.

It can be assumed that the linear trend of the entire signal recording can help define the user's reactions to individual tones in a color-modified virtual gallery environment, especially in identifying individual points on the recorded curve. This procedure will be applied in future research that builds on this basic experiment. Other attributes that may affect the user's physiological changes and that are not considered in this practical research are discussed in the next chapter. In future research, attention will also be focused on individual aspects and analysis of work with individual lie detector sensors. However, the practical use of color and human vision in the VR environment described in this experiment can be assumed in many scientific and commercial fields.

8. Discussion and Conclusion

This experiment is the first to focus on the field of color vision and human vision in a virtual reality environment from the point of view of the color perception of a user embedded in a VR environment. The text mentions the creation of digital twins of actual works of art. Another topic is the realization of modifying the VR environment in terms of color. In a positive reaction, the stimulation of changes using an experiment to capture the color change of the environment of the sensors of the lie detector. There is high potential for different color and computer vision research in digital twin research. That is also related to work with color models and spaces (gamut), which significantly influence the final result of the reproduction of the work of art. [31] **HSV** and **HSB** models are closest to human vision but can always be applied. [32,33] Two basic color models, **CMYK** and **RGB**, were applied in this research. Especially since the original artwork was created with physical colors and the digital display works with light in the **RGB** color model. Table 1 subsequently shows their values used in other parts of the experiment.

The subject of this research is mainly working with the RGB color model, which is used to modify the color environment in VR. This environment contains digital twins of the artworks. In this VR environment, smooth transitions of color tones and sudden changes in the environment to absolute **RGB** values were created. In the Unity engine, a smooth transition of the object's color to another color was achieved using a **C# Script**. The required colors were entered in the form of 3

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sheets. Each of the sheets contained one of the **RGB** color components in the same order in which these colors were displayed and modified in turn:

```
public int[] colR = { 0, 255, 147, 221, 255, 106, 255 };
public int[] colG = { 255, 0, 112, 160, 0, 90, 255};
public int[] colB = { 0, 255, 219, 221, 0, 205, 255};
```

It was added to the **1** variable "**currentColor**" and the parameters of the following colors were obtained from the lists of colors that we store in the variables "**nextR**", "**nextG**" and "**nextB**".

Additional procedures are provided in this chapter. It is necessary to mention that this is one of the options for achieving the need for color modifications. In addition to using the **#C Script**, you can consider applying animation for color modification in the *Unity engine*.

The **polygraph** was chosen to measure a user's reaction embedded in a VR environment. Here was the premise of **recording physiological changes in connection with the reaction to a color change in the environment**. As part of a search of professional publications, similar use of a lie detector has not been found to date, as well as the measurement of a **human reaction to a color change in a VR environment**. Therefore, it was impossible to base the research on previous data in this experiment. So far, the research is mainly aimed at criminology, law, and psychology. [34–37] Although the field of color psychology is the focus of much research, none has yet been conducted in the context of this presented research. [37–41] That research aimed to determine whether the measurement of human perceptions by the sensor lie detector in a VR environment can be evaluated and how the measured data can be evaluated. The *Polygraph LX6* from the *Lafayette Instrument POLYGRAPH company* was used in the research. *SW Lafayette Polygraph System 11.8.5* was used to record sensor signals and their primary output. A user embedded in a VR environment of the virtual art gallery was scanned by the following sensors types: **P1** Abdominal Respiration trace; **P2** Thoracic Respiration trace; **PL** Photoelectric Plethysmograph; **SE** Activity Sensor; **GS** Electrodermal Activity (EDA). These sensors are specified in more detail in section 6. As part of the discussion, it is necessary to mention that the basic signal measurement of these sensors was carried out. A separate analysis of signals from these sensors and their other attributes represents another challenge for future research concerning color and human perception in a VR environment.

The results of this research are presented in section 5 and 7. The section dealing with the programming part of the color modification experiment in the VR environment describes the creation of a **#C Script** procedure created directly for this research. This pivotal part of the research is also the basis for the following measurement of physiological changes in the recorded **physiological sensors**. Due to the many possibilities of analysis, processing, and interpretation of the obtained data from the lie detector, extensive research was carried out on these possibilities. Currently, the subject of scientific research is various processing options rather than just the usual statistical methods of data set processing. [42], [42] In this work, however, classical statistical procedures were used to analyze lie detector data to find an essential procedure for this issue. In time interval of 18 minutes, the total minimum value of $^{a}T_{min}$ and maximum value $^{b}T_{max}$ for individual sensors were determined. The next step was the definition of intervals for individual modifications of absolute RGB colors: **G(255)** G_{min} | G_{max}; **R(255)** R_{min} | R_{max}; **B(255)** B_{min} | B_{max}. All these values were given in Table 2 in this text. These values are also shown graphically in Figure 9, which visually shows the differences of these values in the intervals of the individual displayed RGB colors and the total interval of the $^{a}T_{min}$ and $^{b}T_{max}$ of all lie detector sensors.

The differences in values were shown in Table 3. In Figure 9, the values of the **GS Electrodermal Activity (EDA)** sensor were not shown. The measured values of this sensor differ significantly from others. **"Time series statistical methods"** were used for this sensor and recording evaluation, which proved to be more suitable in the case of this sensor. Subsequently, a **linear continuous trend** was calculated: **GS:** y = 58,461x + 4E+06. This procedure of evaluating the measured data is illustrated in section 8 in Figure 10.

The above procedures of data analysis and their interpretation proved to be suitable for evaluating the data in this experiment. This text describes the signal evaluation method for three intervals of sudden color change in a virtual gallery environment. That process makes it possible to evaluate such smooth color transitions in the VR environment's total time interval of color changes: **GS:** y = 58,461x + 4E+06; **P1:** y = 2075,7x + 1E+09; **P2:** y = -44509x + 2E+09; **PL:** y = 156,04x + 1E+09; **SE:** y = -2021,5x + 7E+08. These **linear trends** for all signal recordings from individual sensors will allow the user's reactions to individual changes in color tones to be evaluated according to their points on the recorded curve. These curves are shown in Figures 10, 11, and 12 for individual lie detector sensors. It is likely that with these processes, it will be possible to more easily analyze other attributes associated with the measured signals of individual sensors and the physiological changes related to this. These additional procedures and analyses will be the subject of subsequent research, for which this experiment provides the basis.

In conclusion, it can be stated that measuring and analyzing user reactions to changes in the color environment in VR is possible. In this experiment, a lie detector was used as a detector of response to a change in the environment. This issue requires further research into color and human vision in a VR environment. This issue also calls for further research in sensors and signal processing. However, practical use in the field of research in medicine, psychology, physiotherapy, art, criminology, or forensic science can be assumed. At the same time, these procedures can also be applied in commercial use areas.

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