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A FRAMEWORK FOR COMPUTER SIMULATION OF COLOR CONSTANCY EXPERIMENTS

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Abstract

Color constancy is an important property of the human visual system (HVS), as it allows us to discern the colors of objects independent of the colors of the light that illuminates them. Experimental color constancy has been a long-studied topic in the field of human perception. With the advent of modern technology and an increase in computing power, as well as more accurate display technology, an opportunity to computationally simulate color constancy experiments, rather than relying on physical objects such as paper, occurred. Many experiments, a lot of which using simulated stimuli, have been conducted on the properties of the human visual system regarding color constancy. However, many experiments required the use of specialized equipment or special observation conditions. In this work, we propose a new framework for computer simulation of color-related HVS experiments aimed at the research of color constancy HVS properties. The proposed framework consists of the software to simulate physical properties of illuminants and objects, the software for easy creation of experiments, and a set of best practices for computer monitor calibration. The advantages of the framework compared to the use of physical objects are low computational power, the ability to generate unlimited numbers of test images, the ability to conduct experiments remotely, more flexibility for time-limited test image presentation, and lower cost. The framework has been tested in two simulated experiments. The first experiment tests the sensitivity of the HVS to the changes in the color of the illumination using simulated Mondrian patterns. The second experiment tests the limits of the color constancy properties of the HVS in highly chromatic conditions using color matches on simulated patterns. In the first experiment, 1,800 color pattern comparisons have been made, resulting in a color sensitivity of 2.46°, which is comparable to the range of 2°-3° measured in other published work. In the second experiment, a total number of 3,000 color pattern matches have been conducted, which resulted in 54% of correct matches. The experimental validation shows that the experiments conducted using the proposed color-testing framework are comparable to experiments conducted using physical objects, such as colored papers. Therefore, we conclude that the proposed framework can be used for other color-related experiments requiring human subject evaluation of various color patterns aimed at the HVS color property research.

Keywords: color constancy; human visual system; simulated experiments; color matching.

1. INTRODUCTION

Color constancy is the ability of the human visual system to perceive the colors of objects as constant under different illumination. For example, if one were to observe an object at noon and at sunset, the color of the object would, for the most part, be perceived the same, even though the spectral characteristics of the light would change by a large margin. This phenomenon has been long studied, with numerous experiments being conducted as far back as 200 years ago. In the first half-century, many behavioral and perceptional experiments were conducted to investigate the color constancy property of the human visual system [28, 15, 34, 18, 20, 14]. However, there has been relatively little consensus on the general mechanism of color constancy. Furthermore, recent experiments disproved the existence of color constancy in the traditional interpretation [25, 22]. They stated that it was more plausible not to refer to the color of the object as intrinsic to the material, but to the light/object pair. This discrepancy in the definition of color constancy is one of the pointers to the fact that there still are many areas requiring further study. For this reason, in this work, we focus on methods for easy simulation of experiments regarding different aspects of color constancy. Nevertheless, the physics behind color rendering and interactions of spectral functions is well known. For any location (x,y) in the scene, the light that a sensor can detect p is described by a formula:

$$p_c(x, y) = \int_\omega I(x, y, \lambda)R(x, y, \lambda)S_c(\lambda)d\lambda\,, \qquad (1)$$

where I is the illumination spectral distribution, R is the spectral reflectivity of an object, S is the sensor spectral characteristic (in this case, the cone cells in the human eye), c is the channel (in the case of the trichromatic human eye, it is one of the three different types of cones), and ω is the spectrum (usually constrained to the visual spectrum, from 380 nm to 780 nm). This equation (1) fully defines the stimulation of the human eye. Furthermore, it is apparent that the illumination and reflectance spectral power distributions are very tightly coupled, and that the mechanism of separating them from just three values obtained by different cones is ill posed. This is the reason why color constancy remains a frequently studied topic and many new experiments are conducted.

For all of these new experiments, researchers have had to decide on the way how to conduct them. There are two main ways to conduct any color constancy-related experiment, physically or using some simulation. Physical experiments are conducted so that the subject is placed in a darkened room, with some source of illumination and some objects, for both of which the spectral characteristic is known. Simulated experiments, on the other hand, are conducted so that the objects and lights are rendered using a computer and then presented to the subject on a computer screen. There are inherent tradeoffs that have to be made in each of the scenarios. For simulated experiments, no real lights and papers are used; they are rather rendered using a formula from their measured spectral characteristics. However, this rendering will inevitably include some sort of approximation, as spectral distributions are continuous values that have to be discretized or approximated using some other continuous function, inducing errors. Furthermore, the display the experiment is conducted on has a large impact on the reproduction of colors. Nevertheless, these types of experiments are much easier to produce, and it is a lot easier to ensure reproducibility. One additional benefit, that is often overlooked, is the much lower price of such experiments, as the cost of adequate monitors has gone down, but the price of real Munsell papers can be prohibitively expensive, especially if more than one set is needed. On the other hand, while the physical experiments use real papers and real lights, it is sometimes difficult to accurately measure their true spectral characteristics or to account for their variably over time. Additionally, it can be hard to ensure reproducibility, as the conditions in the room where the experiments are conducted can influence the results much more than with simulated experiments, especially if the room is not completely darkened.

There has also already been some research concerning the perceptional properties of the human visual system on real and pictorial stimuli [23, 24, 19]. However, we believe that the value of simulated experiments, at least as a first step in testing the viability of some experiments, cannot be discarded.

In this work, we describe a framework for computer simulation of color-related experiments aimed at testing the properties of the HVS. Furthermore, we simulate two different color constancy experiments and show that their results are in line with those conducted using physical objects like paper. Thus, we show that simulated experiments can offer valuable insight, at a reduced cost, both financially and time-wise, into the viability of color constancy experiments. In Section 2, we go over some of the experiments that have been conducted to date. In Section 3, we describe the proposed framework.

In Section 4, we describe the setup for our experiments and the experiments that were recreated using the framework. In Section 5, we compare the results of our experiments to those conducted in real-world conditions. Finally, in Section 6, we offer a conclusion.

2. RELATED WORK

Research into the properties of the human visual system and its ability to be, to some extent, invariant to the color of illumination started nearly 200 years ago, with works including [28, 15, 34, 18, 20, 14]. However, modern systematic research started about fifty years ago, with behavioral experiments conducted in [3]. This was the first experiment that directly targeted the perception of color and the effects of color constancy. A lot of research into color constancy and human perception has been done, including numerous areas of research. However, in this section, we will only briefly touch on some types of color constancy experiments and mention a few notable examples of real-world and simulated experiments. As described in [10], color constancy experiments can be roughly separated into six main categories, based on the main question posed by the authors:

1. **How is color constancy physically possible?** These experiments and models try to understand how humans, with trichromatic vision, seem to possess the ability to differentiate between the color of illumination and the colors of objects. In works [26, 8, 17], various linear models are constructed that express the prerequisites for color constancy and the needed degrees of freedom necessary to successfully reconstruct surface colors. There have been several theoretical approaches to this problem, mostly focusing on lightness algorithms [20], linear models, direct estimation of illumination spectra, and using the Bayes' rule. All of these methods, even though different in origin, have some features in common, e.g. they all concur that ideal color constancy is impossible with no restrictions, because the trichromatic eye allows only a three-dimensional representation of the spectrum to be inferred.
2. **What do observers judge?** These experiments focus on the importance of choosing the right criterion that gives the most insight into the nature of color constancy. The right choice helps make the results more interpretable and more consistent, as well as allows for an easier reproduction of experiments. This insight was first revealed in [3]. These experiments are explained in more detail later in the paper. However, a short overview shows that there are many types of such experiments, and their results indicate the varying ability of the HVS to perform color constancy depending on the conditions.

3. **What experimental methods are suitable?** Methods for testing color constancy in subjects were adapted from traditional psychophysical techniques of color naming and color matching by [3] and [33]. After these works, many more indices and performance metrics were suggested, as well as different adaptational conditions. This led to major uncertainty in assessing the performance of experimental subjects. Three commonly used indices are the constancy index *CI*, Brunswick ratio *BR,* and its projection BR_{ϕ}, where the perfect constancy corresponds to the index and ratio of unity, while a complete absence of constancy corresponds to zero. Under this category falls the issue discussed in this work, on whether color constancy experiments can, with a high level of precision, be conducted in a simulated, rather than real-world, environment. State-of-the-art experiments in this area include asymmetric color matching experiments, color naming experiments, achromatic adjustment experiments, discriminating illuminant changes from reflectance changes, and experiments testing the effects of familiarity and memory. However, many of these experiments are afflicted by methodological difficulties, such as inadequate control of adaptational and inferential contributions to the observed performance, badly defined color judgment criteria, circumvention of the experimental tasks by finding shortcuts, etc.
4. **What physical properties are relevant?** In these types of experiments, the objective was to determine which types of assumptions on the properties of the surface spectral reflectances and illumination can be made. One well-known example of such an assumption is the von Kries [35] for color correction. These experiments help determine the limitations of such assumptions. Current research shows that illumination spectral characteristics, spatial ratios of cone excitations, and spatial structure of the scene are, among others, relevant to the task of color constancy. However, this is still a very active area of research.
5. **What neural mechanisms support color constancy?** Here, many experiments were conducted on the neurological level, mostly on the V4 cells in the visual cortex. These experiments include those published in [37, 38, 36]. However, since they fall well outside the scope of this work, they will not be discussed further (An overview can be found in [10]).
6. **Are natural scenes and surfaces special?** Finally, these experiments try to determine whether laboratory scenes, including Mondrian patterns and artificial illumination, differ significantly from real-world scenes. In [5], the authors used photographic colorimetry to produce the first-ever detailed spatial and colorimetric analysis of natural scenes.

The experiments in all of these categories have greatly advanced our understanding of human color constancy. They allowed us to better define the theoretical requirements for achieving color constancy; the number, and variety of color constancy experiments has greatly increased. Numerous neural mechanisms have been identified, and our understanding of them has increased. However, there still remain significant unknowns and uncertainties in this area, such as color constancy in scenes with non-uniform illumination, and the problems with varying degrees of color constancy reported by previous studies.

The first systematic experiments were conducted on real papers with real sources of illumination, with experiments conducted in [3, 4]. This trend of real-world experiments continued for some time. With the increase in computational power and improvements in display technologies, experiments started to be conducted on computer monitors with simulated papers and sources of illumination. However, with the increased popularity of simulated experiments, several experiments [23, 24] were conducted, showing that some lightness illusions produced by real-world implementations [1, 2] cannot be seen. For these reasons, some color constancy experiments, including two that focus on the deficiencies of color constancy [25, 22], use only real-world Munsell papers. Furthermore, the authors of these experiments later computed the metameric mismatch volumes [21] of those papers under different illumination conditions present in the experiments to draw some conclusions [22]. However, due to the nature of the illumination conditions and the semi-darkened environment, in which the experiments were conducted, such computations can be less accurate. For this reason, and to insure easier and cheaper reproducibility, it would be beneficial if such experiments could be simulated. Furthermore, other experiments, some of which more recent, conducted on the properties of the human visual system and color vision, such as [30, 31, 32], use simulated Mondrian patterns with different illumination. Figure 1 shows an example of both a simulated and a real-world experiment. Some research has been conducted regarding the viability of simulated experiments, which shows that under real conditions, some types of experiments are performed better than in a simulated environment [19]. Nevertheless, simulated experiments give us a considerably cheaper and faster option to try out, at the very least, the viability of new experiments, before implementing more complex real-world experiments. Thus, it was the objective of this paper to create a method that would allow for inexpensive preliminary testing of color constancy properties in humans, using simple measuring strategies and previously measured spectral characteristics of real-world objects, e.g. Munsell papers [6].

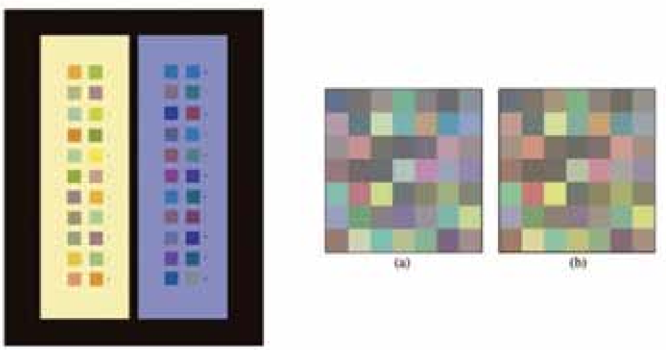

Figure 1. Examples of real-world and simulated experiments. The left image shows a real-world asymmetric matching experiment. The image was taken from [25]. The right image shows a simulated relighted Mondrian pattern. This image was taken from [30].

Slika 1. Primjer fizički implementiranog te simuliranog eksperimenta. Lijeva slika prikazuje fizički implementirani eksperiment s asimetričnim podudaranjem. Slika je preuzeta iz [25]. Desna slika prikazuje simulirani eksperiment s različito osvjetljenim Mondrian uzorcima. Slika je preuzeta iz [30].

3. FRAMEWORK FOR COLOR-RELATED EXPERIMENTS

The objective of the paper was to create a framework that could be used to simulate different types of experiments. In this section, we describe the proposed framework and its components. The framework is composed of three parts. The first is the software used to simulate the physical properties of illuminants and objects, and the way color that reaches the HVS is produced. The second part of the framework is the software that allows for an easy, reproducible and extensible way of defining new color-related experiments. The third component is a set of instructions and best practices on how the computer displays should be set up for the experiments. These three components facilitate the implementation of various color-related experiments used for the testing of the properties of the HVS. The rest of the paper will focus on the conducted experiments to show the performance of the simulation framework in real experiments.

The framework is based on the colour-science [7] library that is used to conduct all spectral calculations, as well as provide some standardized light sources, which can be used in the experiments. Furthermore, spectral measurements of the publicly available [29] Munsell color papers [6] are used to simulate physical papers. We use Munsell papers as the base for simulated experiments, as they are most commonly used in experiments involving physical papers conducted so far. Finally, common light sources that are used in many experiments are also provided in the framework, while other light sources specific to experiments can be provided as a spectral function. The rendering of the color triplets is done by using color-matching functions, which can again be specified by the user. Finally, the color triplets are produced using the discretized version of Equation (1):

$$p_c(x,y) = \sum_{\lambda=\omega_0}^{\omega_1} I(x,y,\lambda)R(x,y,\lambda)S_c(\lambda) \quad (2)$$

where ω_0 and ω_1 are the lowest and the highest wavelengths respectively, sampled at one-nanometer increments, while the rest of the symbols in Equation (2) are the same as those in Equation (1). The aforementioned Munsell papers are used as the reflectances *R* in the formula, while the illuminants *I* and spectral sensitivity functions *S* are usually dependent on the conducted simulated experiment. The wavelengths *λ* are most commonly sampled set to the visual spectrum, i.e. from 380 to 780 nm.

Once the patterns, lights, experimental layout, and criterion have been defined, the framework offers a simple way to display the specified experiment to the subjects through its interface. Furthermore, it allows the experiments to have a time constraint, to test properties that are tied to purely perceptional layers of the HVS. Finally, the framework allows the users to select some of the more commonly used color spaces for displaying the experiments, such as sRGB and P3, by using the included color transfer matrices for the XYZ color space, while others can also be supplied. These color spaces are important, as they define the ways that the colors will be reproduced on the computer display, on which the experiments will be shown. These monitors should be color calibrated in some way, for which a color calibration tool is strongly advised. For the experiments described in Section 4, we used a Spyder Elite 4 Calibration tool that allows us to create reproducible experiments by eliminating the variability of the computer displays.

Once the framework was implemented, we used it to simulate two color-related experiments testing the properties of the human visual system. We did this to demonstrate the viability of our framework for the simulation of color-related experiments. We then analyzed the results that were obtained, and compared them to experiments using physical objects, such as papers that were published in other works, to show that simulated experiments get comparable results.

4. FRAMEWORK APPLICATION FOR COLOR EXPERIMENTS

In this section, we describe two specific experiments related to the research of color properties of the HVS, which demonstrate the usefulness of the proposed experimental framework. We describe in detail the experiments that were simulated, the criteria that were used for each of them, as well as some theories needed to describe the results. One experiment that was simulated was the asymmetric color matching experiment using Mondrian patterns similar to the one described in multiple works [4, 31, 32, 30]. This was implemented to perform the initial viability study of our framework on the task of determining the minimum distance between the illumination the human eye is capable of discerning. One such experiment is shown on the right side of Figure 1. Once those experiments were conducted, we moved on to the experiments described in [25, 22]. We selected those experiments as interesting, as they are some of the newer experiments that deal with the limitations of the human visual system when it comes to color constancy. As such, they allow us to test whether simulated experiments match the results of experiments using physical colored papers and serve as a viability test for more complicated real-world experiments.

4.1. Mondrian Experiment

The first type of experiment that was implemented was a simple Mondrian and surround experiment. It was designed to test whether the subjects were able to distinguish between the global or local illumination change in a simulated condition. The objectives of this experiment were twofold: to validate the results of previous work on color perception, which states that a healthy human eye is capable of distinguishing the angular distance of at least 2°-3°, and to test the viability of simulated experiments for this color constancy-related task. The experiment was conducted using different RGB computer monitors and on multiple subjects (n=6). The following subsections describe the stimuli and the procedure, the experimental setup, the observers, and the performance measures that were used.

4.1.1. Stimuli

The stimuli were generated using a Python script using the "colour-science" package [7] that allows for easy manipulation of spectral data needed to realistically generate the stimuli. The Mondrian patterns consisted of either 25 (5 × 5) or 49 (7 × 7) patches, each side covering a visual angle of 5° or 3°. The patches were drawn from the Munsell matte [6] patches, and illuminated by daylight of correlated color temperature 6500K as a baseline. The pattern was set into a gray surround, illuminated by the same light. The patches were sampled so that they are not similar in color to the surround [27, 11]. Subsequently, the subjects were shown another Mondrian pattern, this one illuminated by a new illuminant, that of daylight with shifted correlated color temperature. However, the surround, or one patch at random, was illuminated either by the same new illuminant or by a different illuminant. The subjects were then asked whether the illumination changed constantly over the whole scene or whether the new scene was illuminated by more than one illumination. Three versions of this experiment were conducted: one where the subjects observed the first and second Mondrian patterns indefinitely (untimed); the second where they only observed the second pattern indefinitely, while they were only shown the first pattern for a second (untimed baseline); and finally, the third, where they were shown both patterns for only a limited amount of time (timed), for a second at the most, after which the subjects had to decide upon their response. The subjects were shown 96 random Mondrian patterns for each experiment. Each experiment took 5-10 minutes on the average. Examples of these sessions are shown in Figure 2.

4.1.2. Experimental setup

All the subjects were shown the Mondrian patterns on the same Phillips 272B8Q IPS RGB monitor, which was calibrated to display the colors accurately. The resolution of the screen was 2560 × 1440. The display was calibrated using the Spyder Elite 4 Calibration tool, which itself was calibrated in the factory. The monitor showed errors with calibration in the CIE xyY coordinates of less than 2° in color reproduction. Additionally, two observers used two different monitors: one Apple iMac 2015 integrated IPS RGB monitor, with the resolution of 5120 × 2880 (using Apple Retina scaling to 2560 × 1440), calibrated using the same tool, with errors of less than 1°;

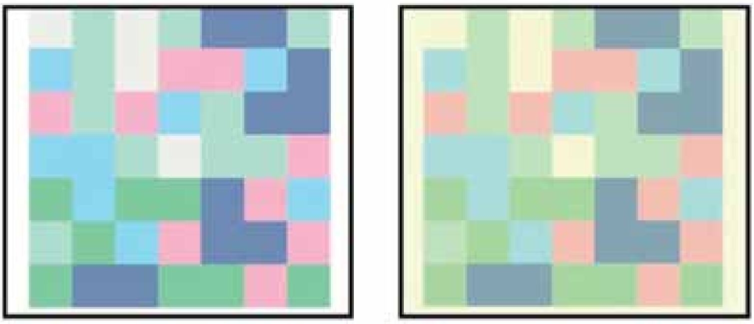

Figure 2. An example of a Mondrian pattern and surround illuminated by white light (left), and the same Mondrian pattern illuminated by two lights, one for the pattern and one for the surround (right). Note that this is a random pattern used for illustration, with no constraint on the edge patches [27, 11].

Slika 2. Primjer Mondrian uzorka i okruženja osvjetljenog s bijelim (lijevo) te isti Mondrian uzorak osvjetljen s dva izvoram jedan za uzorak, drugi za okruženje (desno). Važno je naglasiti da je ovaj nasumični uzorak generiran bez ograničenja za rubne kvardate [27, 11].

and one Apple MacBook Air 2021 laptop with IPS RGB monitor, with the resolution of 2560×1600 (using Apple Retina scaling to 1280×800) that was not calibrated after the fact. All the white points were set to the correlated color temperature of 6300K.

4.1.3. Observers

The subjects for this experiment were taken from a pool of faculty staff. They included 6 individuals aged 23-30, with 4 male and 2 female participants with normal color vision. All the participants except the two co-authors were unaware of the purpose of the experiments. All subjects were tasked with selecting (using the “y” and “n” keys on a keyboard) to tell whether the illumination changed constantly over the whole scene or whether multiple illuminants illuminated the scene. The procedure was the same for all three sessions (untimed, untimed baseline, and timed).

4.1.4. Performance Measure

To test the performance of the subjects on the given task, the angular distance, described in Equation (3) between the illuminations in the first and the second pattern, was used.

$$err_{ang} = \cos^{-1}\left(\frac{\boldsymbol{e}_r \cdot \boldsymbol{e}_p}{\boldsymbol{e}_r \boldsymbol{e}_p}\right), \quad (3)$$

where e_r and e_p are the RGB values of the two illuminants that were used, and · is the scalar product of the illumination vectors. The RGB values were obtained from the spectral characteristics using the CIE 2° 1931 color matching functions to obtain the XYZ values that were then converted to sRGB for display.

This value was 0 when the illuminant was the same and increased the more the two illuminants were different. For each subject, simple logistical regression was fitted on the angular distances, where the labels indicated whether they thought that the illumination was uniform or not. This allowed us to find the decision boundary between what each subject considered the same illumination while allowing us to eliminate some outlier behavior that could have happened because of the subject error caused by reduced attention. Furthermore, we conducted a study focusing on the difference in the angular distances based on the shift of the second illuminant towards blue or red parts of the spectrum from the first illuminant. We discuss the findings in Section 5.

4.2. Asymmetric Least Dissimilar Matching Experiments

The second experiment that was implemented was the experiment described in [25, 22]. These experiments were designed to test the color-matching properties of the human visual system under different illumination conditions. They try to show that it is impossible to achieve an exact color match under different chromatic lights. There are three main differences between the original experiment and the previously described experiments. First, the experiment does not use Mondrian patterns, but instead focuses on individual Munsell papers in the test and match fields. Furthermore, the experimental setup uses lights of very different spectral characteristics than the daylight lights of varied correlated color temperatures, which tests the human visual system in difficult conditions. The spectral characteristics of these lights can be seen in Figure 4. Finally, and most important for this work, these experiments were conducted on real-world papers, using real lights in a semi-darkened room. For these reasons, this experiment is an ideal candidate to show that difficult real-world color constancy experiments can also be simulated while retaining some level of performance. The next subsections describe the stimuli and procedure, the experimental setup, the observers, and the performance measures that were used.

4.2.1. Stimuli

The stimuli were again generated via a Python script using the “colour-science” package [7]. The experiment consists of two sets of 20 identical Munsell papers, referred to as the test and match sets positioned into a grid over a gray background. Each set was illuminated by one of the 5 chromatic illuminants. Both the Munsell papers and the illuminants were the same as in [22]. Note that this shows the first benefit of the simulated experiments, as it was easy to reproduce the experiment without the need to purchase specialized equipment. Munsell paper spectra were obtained from the dataset of Munsell papers [29], while the illumination spectra were obtained from [25]. To simulate the semi-darkening of the room, a small amount of daylight spectra (at 10% of the power of the main light) was added to all the illuminants, to match the setup in the original paper (as can be seen on the left side of Figure 1). Figure 4 shows the comparison between the original Munsell papers and the light spectra [22], and the simulated papers and the used light spectra. The experiments were conducted to mimic the procedure described in [25], where each paper, illuminated by each of the 5 lights, was used 3 times in the test field and 3 times in the match field (this results in each paper being selected for testing and matching 75 times). The current test paper, for which the subjects had to find the least dissimilar match, i.e. the paper that looks most similar in the match field was indicated by displaying a small black “x” over it (unlike the laser pointer used in the original experiments). We follow the notation from [25] when referring to the illuminations, with the neutral, yellow, red, green, and blue lights having designations N, Y, R, G, and B respectively. Illumination conditions for a session are designated as the "test-match", e.g. N-Y (or NY) means that the test set was illuminated by neutral light N, and the match with yellow light Y. Figure 3 shows the illumination condition (Y-B) and the same scenario from the original paper.

4.2.2. Experimental setup

Subjects were shown the test and match fields in a darkened room, on a calibrated Apple MacBook Pro 2021 16' computer monitor, whose luminance was set to a maximum of 75 nits, so as not to over-saturate the eye. The resolution was 3456×2234 (using Apple Retina scaling to 1728 × 1117). The display was calibrated using the Spyder Elite 4 Calibration device, with errors of less than 1°. The stimuli were converted to the XYZ using the CIE 2° 1931 color matching functions, after which they were converted to DCI-P3 color space, which matched the display. To match the original experiment, the least dissimilar match criterion was used.

4.2.3. Observers

The subjects for the experiments were again taken from the faculty staff. The number of subjects was smaller than in the original experiment, numbering only

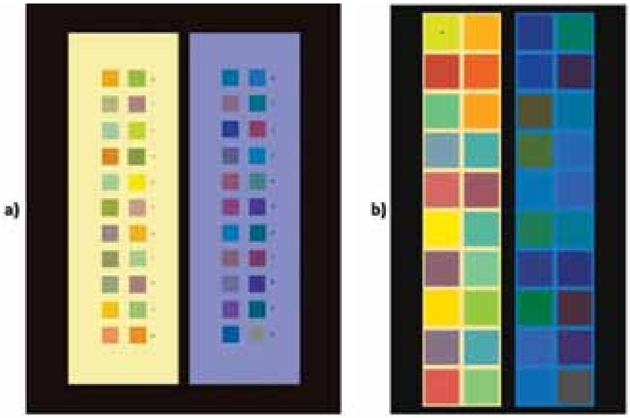

Figure 3. An example of an illuminant condition Y-N from a) original experiment [22] and b) simulated experiment. The colors in the second image might look different, since they were rendered in a DCI-P3 color space, which is less frequently used in commercial monitors.
Slika 3. Primjer N/Y uvjeta osvjetljenja iz a) orginalnog eksperimenta [22] i b) simuliranog eksperimenta. Boje u drugoj slici mogu izgledati drugačije, zato što su generirane u DCI-P3 prostoru boja, koje se koristi rjeđe u komercijalnim monitorima.

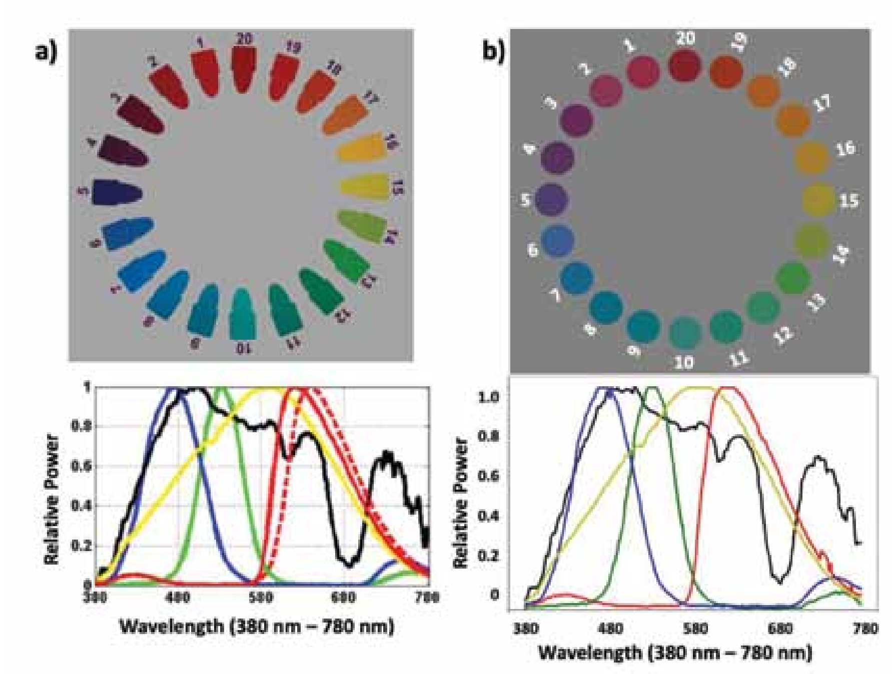

Figure 4. (Top) A comparison of the a) original photography of Munsell papers [22] and b) our computationally rendered Munsell papers under flat white illumination. The same Munsell papers from the original [22] were used, but the appearance might differ due to the difference in illumination conditions while taking the picture and used for rendering. (Bottom) A comparison of the illumination light spectra used for illuminating the test and match areas a) from the original paper [22] and b) used in our simulated experiments. Line color corresponds to the illumination color as seen by the human eye.

Slika 4. (Gore) Usporedba a) orginalne fotografije Munsell papirića [22] i b) računalno generirani Munsell papirići pod idealnim bijelim osvjetljenjem. Munesll papirići korišteni u orginalnom članku [22] su korišteni, no razlike u izgledu mogu postojati zbog razlike u osvjetljenju slike te osvjetljenja korištenog pri generiranju. (Dolje) Usporedba spektara osvjetljenja korištenih za osvjetljavanje ispitnih i podudarajućih regija a) iz orginalnog članka [22] i b) korištenih u simuliranim eksperimentima. Boja linija podudara se s bojom osvjetljenja kako ih ljudsko oko vidi.

2. One of the subjects was aware of the purpose of the experiment. However, this was considered to suffice to show that the results were consistent to those produced by the original experiment (where the number of participants was 4). One session (which included 3 iterations over the same illumination conditions) took about 10 minutes (Unfortunately, the ongoing COVID-19 reduced the number of subjects available, especially for long experiments such as this one).

4.2.4. Performance Measure

In this work, we will focus mostly on the metrics presented in the original paper [25], where the average match and mismatch rates are studied. The match rate for a lighting condition is simply the percentage of the match papers that the subject selected, corresponding to the paper in the test field that was highlighted. Furthermore, the metamer mismatch indices were also calculated again for the illumination conditions and the Munsell papers. However, since we were able to vary the amount of background light present in the simulated semi-darkened room, we also present metamer mismatch indices [21] for those conditions. A metamer mismatch index is defined for the shift in illumination from one illuminant to another. Each illuminant produces an object-color solid, which comprises all colors that may be produced under it. Similarly, an illuminant shift creates an object-color solid based on the colors that are metameric under those two illuminants. The object color solid is the collection of all the possible spectra that produce the same XYZ response under the first illuminant. This means that different spectral functions can seem the same to the human eye under one illumination, and entirely different under the second. For a more in-depth analysis and explanation of metamer mismatching in color vision, we refer the readers to the papers by *Logvinenko et al.* [21, 22]. In Section 5, we present the match rates for our experiment, as well as the metamer mismatch indices for some different lighting conditions.

5. RESULTS

In this section, we present the results of both simulated experiments implemented and tested using the proposed framework. For the Mondrian experiment, the focus was set at confirming the findings presented in [13, 16, 12, 9] while using the simulated Mondrian patterns similar to those proposed in [31, 32, 30]. The asymmetric least dissimilar matching experiment reproduces the results of the experiment described in [25, 22], and thus demonstrates that simulated experiments are a viable strategy for conducting preliminary color constancy experiments.

5.1. Mondrian Experiments

As it was described in Section 4, the Mondrian experiments were designed in such a way as to test the limits of human perception in detecting a shift in illumination. After the subjects had conducted the experiments, we collected the data and processed them in the way described before. We looked at the three variations of the experiments separately; for each one, we calculated the mean and the standard deviation for the angular distance between illumination that the human visual system could discern. These results are shown in Table 1. A plot of the results gathered from one subject is shown in Figure 5. The bottom part of the graph is the shift towards blue (increase in temperature), while the top shows the red shift (decrease in temperature). The blue shift was more difficult for the observer to spot than the red shift.

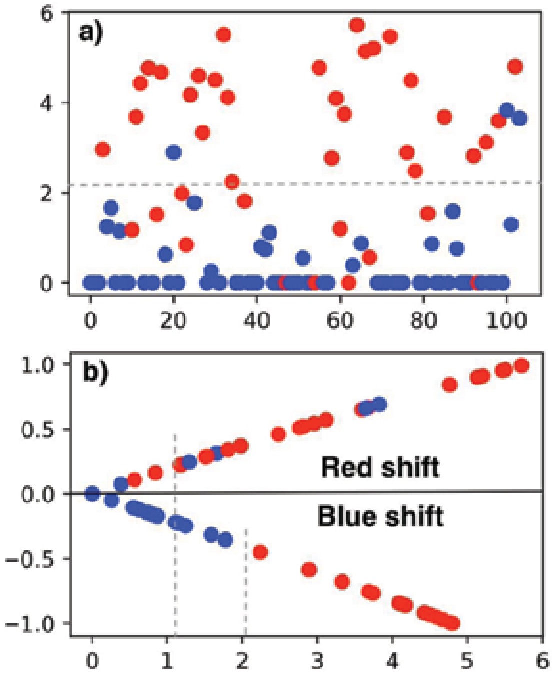

Figure 5. An example of results for Observer 1 for the timed Mondrian experiment. Red dots represent the cases when the observer said that the illuminants were different, while blue dots indicate that the observer said that the illuminants were the same. The gray line shows the boundary when outliers are discounted. a) Plot of the index of the Mondrian in relation to the angular distance. b) Plot of the angular distance in relation to the shift of the illuminant from the normal baseline.

Slika 5. Primjer rezultata za Promatrača 1 za vremenski ograničeni Mondrian eksperiment. Crvene točke označavaju slučajeve kada je promatrač rekao da su osvjetljenja različita, dok plave točke ozačavaju slučajeve kada nije mogao vidjeti razliku. Siva linija označava granicu kada su stršeće vrijednosti uklonjene. a) Graf kutne udaljenosti u ovisnosti o indeksu Mondirana. b) Graf kutne udaljenosti osvjetljenja u ovisnosti o pomaku osvjetljenja od standarnog osvjetljenja.

The obtained results are in line with the results provided by other studies, like [13, 16, 12, 9], which deal with real-world situations. It is also interesting to note that as long as the monitor was adequately calibrated, the results stayed mostly the same, with variations consistent with that of the subject, not the equipment. This shows that our framework enables that, in the future, larger-scale testing and experiments with more participants could be conducted much easier. Furthermore, Figure 5b shows the difference in the discriminatory ability of one of the observers. The bottom part of Figure 5b corresponds to the shift towards blue light (increase in temperature), while the top shows the red shift (decrease in temperature). Two gray lines indicate different decision boundaries for the blue and the red shifts. It can be seen that the red shift is much more noticeable than the blue one, as indicated by the first vertical gray line located at approx. 1° for the red, and 2° for the blue shifts. This was true for all the subjects to a varying extent. This means that, at least for our subjects, the shift toward red hue was much more noticeable than the shift towards blue. When asked, the subjects' responses did confirm this verbally as well.

Table 1. Mean minimum angular distance between illuminants that the subjects judged as different for all three types of Mondrian experiments.
Tablica 1. Prosječna minimalna kutna udaljenost između osvjetljenja koju su ispitanici ocijenili kao različitu za sva tri tipa Mondrian eksperimenata.

	Untimed	Untimed baseline	Timed
Mean	2.42	2.52	2.43
Std	0.50	1.04	0.81

5.2. Asymmetric Least Dissimilar Matching Experiments

In this experiment, we conducted the Least Dissimilar Matching Experiments proposed in [25]. However, our experiments were simulated. We used the Munsell papers that were used in the original experiments, excluding the gray ones, as well as only 5 out of 6 lights (light R2 was removed since it is similar to R1), as was done in [22]. Figure 6 shows the CIE xy values of the original Munsell papers under different lights and the Munsell values under the simulated lights, as well as under the simulated lights with added daylight, to simulate the effects of a semi-darkened room. We can see that there is some deviation in the values in the first two images, but those can be attributed to the errors in the measurement of the spectral distributions of the lights and the Munsell papers. This also has a small effect on the metamer mismatch indices shown in Table 2, taken from the original. What is more important is that the addition of a small amount of daylight shifts the gamut of colors for the chromatic illuminants, and also reduces the metamer mismatch indices, as shown in Table 3. However, we can still see that the metamer mismatch indices of some light transitions are high for all the papers, which means that the same effects as in the original real-world experiment should be observed.

Table 4 presents the averaged results for both observers on the 25 lighting conditions. We can see that these results show a large drop-off in the matching performance when highly chromatic illuminants are used, which is consistent with the results obtained in real-world experiments (Table 5, [25]). Figure 7 shows the results of the first observer in 25 different illumination conditions. These results are visually consistent to those produced by real-world experiments [25] (one example from the original is shown in Figure 8). All of these results indicate that the simulated experiments follow the same trend as the original experiments when it comes to finding the exact match in a highly chromatic scenario. The averaged match rate for simulated experiments is 54% with the standard deviation of 0.23, while the averaged match rates for experiments using physical experiments are 47% with the standard deviation of 0.25. We can thus intuit that these experiments, although they are not a perfect simulation of the real-world, can point to the same results as their real-world counterparts. From here, real-world experiments can be conducted to test real-world performance. This is however out of the scope of this study, as the objective was to create a simple method that may be used for preliminary testing of some types of color constancy experiments. Furthermore, the experiments were easier to conduct and allowed for more variation in the positions of the Munsell papers between sessions. Thirdly, the simulated experiments allowed us to vary the conditions in which the papers were shown by changing the amount of background light that was permitted, such as is the case in a semi-darkened environment. This shows the versatility of this type of simulated experiment, which allows for faster iteration and provides many more options to researchers in designing experiments.

Table 2. Metamer mismatch indices for all the selected Munsell papers for select changes in illumination, taken from the original work [22]. Used for comparison with Table 3. NG, NB, NR, GN, GB, GY and GR represent the illumination changes, i.e. NG denotes the change from neutral to green illumination, NB is the change from neutral from blue, etc. Lower values indicate that fewer metameric matches are observed when changing from the first to the second light source.

Tablica 2. Indeksi nepodudarnosti metamernih parova za sve odabrane Munsell papire za odabrane promjene osvjetljenja, preuzeti iz izvornog rada [22]. Koristi se za usporedbu s Tablicom 3. NG, NB, NR, GN, GB, GY i GR predstavljaju promjene osvjetljenja, tj. NG označava promjenu od neutralnog do zelenog osvjetljenja, NB označava promjenu od neutralnog do plavog osvjetljenja itd. Niže vrijednosti ukazuju na manji broj metamernih parova koji su opaženi prilikom promjene iz prvog u drugi izvor svjetla.

Munsell Paper	Illumination Condition							
	NG	NB	NY	NR	GN	GB	GY	GR
1	0.32	0.14	0.0024	5.4	1.1	0.69	0.0023	9.3
2	0.55	0.10	0.0019	6.3	1.2	0.53	0.0019	7.2
3	3.4	0.55	0.0064	7.5	4.1	1.3	0.0059	9.1
4	3.0	0.13	0.0047	5.0	2.3	0.54	0.0026	5.5
5	4.2	0.23	0.0048	5.4	3.9	0.70	0.0042	5.9
6	5.9	0.77	0.0088	11	5.7	1.4	0.0082	9.6
7	6.3	0.37	0.0056	8.5	4.9	0.86	0.0051	6.6
8	5.5	0.96	0.0072	5.6	6.1	1.3	0.0068	6.9
9	4.3	1.5	0.0089	6.1	6.3	1.9	0.0086	9.8
10	4.2	1.9	0.0090	6.3	6.7	2.1	0.0097	11
11	7.5	3.4	0.016	14	8.4	2.8	0.017	14
12	3.9	2.6	0.0102	7.0	6.8	2.5	0.011	13
13	3.6	2.9	0.0105	7.0	6.7	2.7	0.011	13
14	3.7	2.9	0.0110	7.5	6.9	2.8	0.012	14
15	3.5	2.8	0.0117	9.2	6.5	3.0	0.013	15
16	1.4	1.5	0.0075	7.8	4.0	2.0	0.0083	15
17	1.2	1.2	0.0074	9.9	3.4	1.9	0.0079	15
18	0.81	0.84	0.0064	10	2.7	1.6	0.0066	14
19	2.0	1.29	0.0078	22	4.0	1.9	0.0074	16
20	0.98	0.65	0.0051	15	2.9	1.4	0.0054	13
Flat Grey	13	4.1	0.021	47	9.7	3.1	0.018	20
Average Excluding Flat Grey	3.3	1.3	0.0077	8.8	4.7	1.7	0.0077	11.1
Average Including Flat Grey	3.8	1.5	0.0083	10.6	5.0	1.8	0.0082	11.6

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Table 3. Metamer mismatch indices for the Munsell papers for select changes in illumination (the changes were taken from the original paper[22]) with an addition of background light of low intensity. These values are smaller than those presented in Table 2, but more representative of real-world scenarios, because of the added background light. However, they still have generally the same trend. The notation of the Munsell papers is taken from [29]. NG, NB, NR, GN, GB, GY and GR represent the illumination changes, i.e. NG denotes the change from neutral to green illumination, NB is the change from neutral from blue, etc. Lower values indicate that fewer metameric matches are observed when changing from the first to the second light source.
Tablica 3. Indeksi nepodudarnosti metamernih parova za Munsell papire za odabrane promjene osvjetljenja (promjene preuzete iz izvornog rada [22]) uz dodatak pozadinskog svjetla niske snage. Ove vrijednosti su manje od onih prikazanih u Tablici 2, ali su reprezentativnije za stvarne scenarije zbog dodanog pozadinskog svjetla. Međutim, još uvijek imaju uglavnom isti trend. Notacija Munsell papira preuzeta je iz [29]. NG, NB, NR, GN, GB, GY i GR predstavljaju promjene osvjetljenja, tj. NG označava promjenu od neutralnog do zelenog osvjetljenja, NB označava promjenu od neutralnog do plavog osvjetljenja itd. Niže vrijednosti ukazuju na manji broj metamernih parova koji su opaženi prilikom promjene iz prvog u drugi izvor svjetla.

	NG	NB	NY	NR	GN	GB	GY	GR
DRP5014	0.20	0.15	0.01	1.57	0.53	0.97	0.56	8.11
BRR4014	0.07	0.05	0.00	0.72	0.20	0.24	0.21	3.43
DRR5016	0.08	0.03	0.00	0.46	0.18	0.17	0.20	2.91
BYR7014	0.27	0.11	0.00	0.39	0.42	0.52	0.47	5.44
DYR7014	0.22	0.03	0.00	0.24	0.20	0.18	0.24	2.69
BYY8014	0.12	0.04	0.00	0.08	0.09	0.15	0.11	1.69
DYY8512	0.15	0.09	0.00	0.18	0.06	0.20	0.06	0.98
BGY7012	0.35	0.09	0.01	0.84	0.22	0.30	0.23	3.84
DGY6012	0.45	0.20	0.01	1.39	0.45	0.81	0.55	6.88
BGG5010	0.51	0.39	0.01	2.07	0.71	1.52	0.71	9.21
DGG5010	0.58	0.48	0.01	1.66	0.77	1.70	0.83	10.07
BBG6010	0.49	0.38	0.01	1.75	0.72	1.50	0.66	10.01
DBG5010	0.69	0.42	0.01	1.21	0.73	1.57	0.71	8.96
BBB5010	0.53	0.35	0.01	0.83	0.59	1.04	0.66	7.24
DBB5012	0.52	0.15	0.01	0.49	0.43	0.61	0.50	5.58
BPB5012	0.44	0.14	0.01	0.62	0.57	0.85	0.67	6.62
DPB4012	0.57	0.46	0.01	1.45	0.86	2.15	0.86	10.50
BPP4012	0.33	0.29	0.01	1.33	0.63	1.50	0.63	6.93
DPP4012	0.22	0.23	0.01	1.35	0.49	1.19	0.55	5.57
BRP5012	0.44	0.31	0.01	2.46	0.88	1.78	1.00	10.60
Average	0.36	0.22	0.01	1.06	0.49	0.95	0.52	6.36

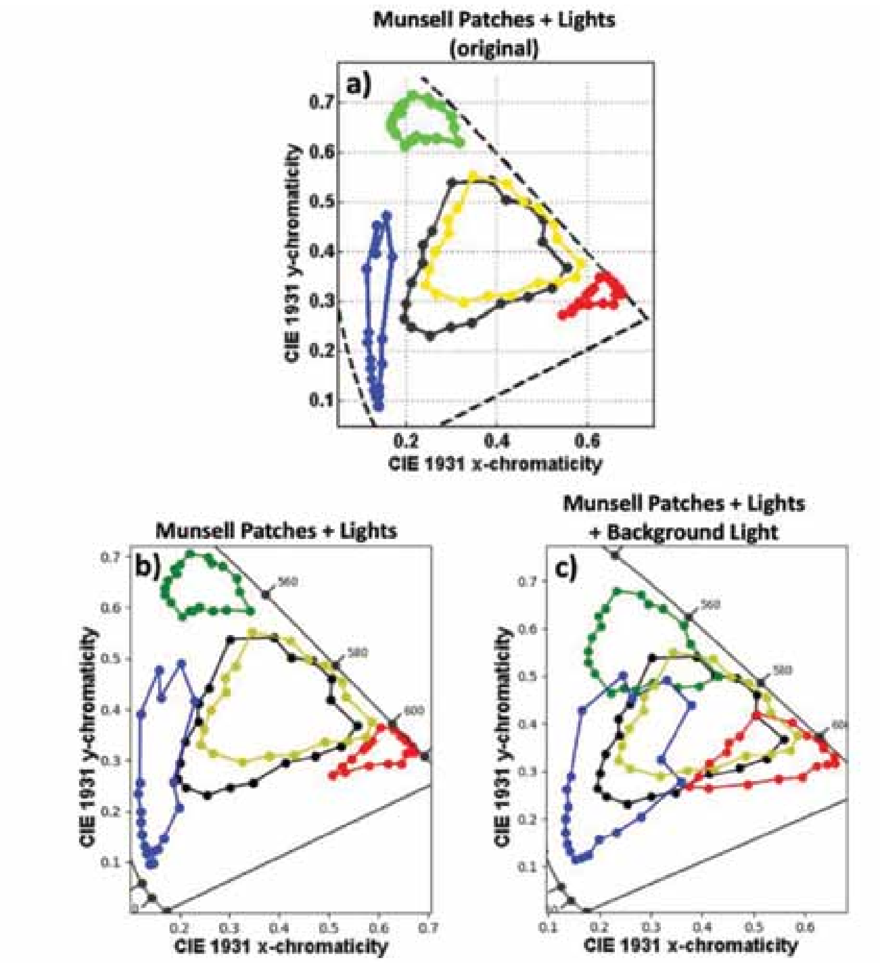

Figure 6. A comparison of the CIE xy values under all illumination conditions of the a) Original Munsell papers [22], b) Simulated Munsell papers, and c) Simulated Munsell papers with added background light to simulate the effects of a semi-darkened room. The color of the lines and dots indicates the color of the illumination (N, Y, G, B, R).

Slika 6. Usporedba CIE xy vrijednosti po raznim uvjetima osvjetljenja a) Orginalni Munsell papiri´ci [22], b) Simulirani Munsell papiri´ci i c) Simulirani Munsell papiri´ci s dodanim pozadinskim ovjetljenjem koje simulira djelomično zamračenu prostoriju. Boje linija i točaka označavaju boju osvjetljenja (N, Y, G, B, R).

Figure 7. A comparison of the results for Observer 1 in the same way as shown in the original paper [25]. Test papers are shown on the abscissa, and the match papers are shown on the ordinate. Each row corresponds to the same test illumination, while the columns correspond to the match field illumination.

Slika 7. Usporedba rezultata Promatrača 1 prikazanih na isti način kao i u orginalnom članku [25]. Ispitni papirići su prikazani na apcisi, a na ordinati su prikazani podudarajući papirići. Svaki red odgovara ispitnom osvjetljenju dok stupci označavaju ovjetljenje podudarajuće regije.

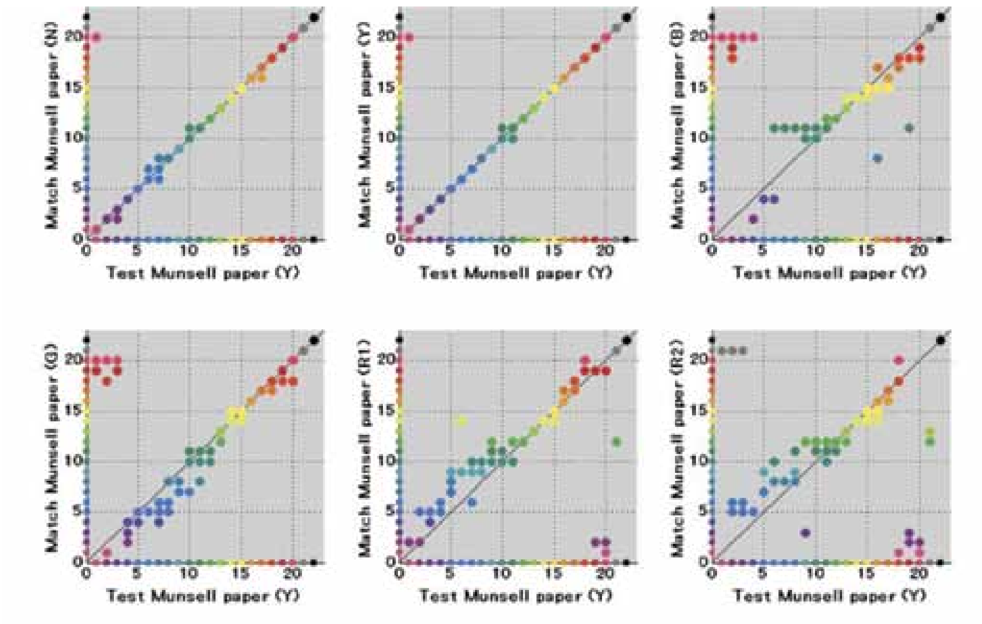

Figure 8. Results for Observer 2 for the yellow illuminant taken from [25], for visual comparison with Figure 7.

Slika 8. Rezultati za Promatrača 2 za žuto osvjetljenje preuzeti iz [25], za vizualnu usporedbu sa Slikom 7.

Table 4. Averaged match rates for the simulated least dissimilar matching experiment. Rows indicate the test illumination, while the columns indicate the match illumination. N, Y, B, G and R headers denote the neutral, yellow, blue, green, and red illumination conditions.

Tablica 4. Prosječne stope podudaranja za simuliran eksperiment najmanje različitog podudaranja. Redovi označavaju testno osvjetljenje, dok stupci označavaju podudarajuće osvjetljenje. Zaglavlja N, Y, B, G i R označavaju neutralne, žute, plave, zelene i crvene uvjete osvjetljenja.

	N	Y	B	G	R	Mean
N	95	80	48	42	52	63
Y	70	88	43	58	60	64
B	66	37	92	47	20	52
G	53	55	42	85	18	51
R	37	51	20	23	76	41
Mean	64	62	49	51	45	54

Table 5. Averaged match rates for real-world experiments [25]. Rows indicate the test illumination, while the columns indicate the match illumination. The original includes light R2, which was removed in subsequent works because it was similar to R1, so it was excluded from this one as well.

Tablica 5. Prosječne stope podudaranja za eksperimente u stvarnom svijetu [25]. Redovi označavaju testno osvjetljenje, dok stupci označavaju podudarajuće osvjetljenje. Originalno je uključeno svjetlo R2, koje je uklonjeno u kasnijim radovima jer je bilo slično R1, pa je i u ovom eksperimentu isključeno.

	N	Y	B	G	R1
N	92	77	39	42	31
Y	80	93	27	41	39
B	40	28	84	31	18
G	56	41	30	78	17
R1	32	41	18	18	76
R2	30	30	14	19	62

6. CONCLUSION

In this paper, we proposed a novel framework for implementing and conducting simulated color-related experiments. The main benefit of the proposed approach is that, unlike experiments that require physical objects, such as paper, experiments can be implemented faster and conducted easier. Furthermore, the simulated nature of experiments allows for an easier variation in the setup of the experiments, e.g. it is easier to vary the lighting conditions, and the placement and arrangement of color patterns in a simulated environment than using physical papers and lights. It is also possible to conduct experiments online over the Internet. The framework is implemented in an easily extensible way, thus allowing for different experiments to be implemented using it while requiring only a decently calibrated consumer-grade computer monitor for displaying the experiments.

Using the proposed framework, we conducted and presented two simulated experiments testing different aspects of the color constancy ability of the human visual system. We conducted these experiments to show the simulated experiments' viability and ease of implementation. The first experiment used Mondrian patterns (similar to those presented in [31, 32, 30]) to test the sensitivity of the HVS to light changes in illumination. The obtained results were between 2°-3°, which is consistent with the results of many studies, including those presented in [13, 16, 12, 9].

The second experiment implemented the least dissimilar matching experiments presented in [25, 21]. These experiments were originally implemented using real papers and illuminants, and conducted in a semi-darkened room. However, this introduces issues with reproducibility, both because exact conditions cannot be reproduced and because it can be expensive and difficult to obtain Munsell papers and light that match those used. For this reason, we simulated the experiments and gathered the results. We showed that our results follow the same trend as those presented in the original studies, with an average match rate of 54% for simulated experiments, compared to 47% in the original.

The obtained results for both experiments show that such experiments can be conducted in a simulated environment using the proposed framework. This makes them easier and cheaper to implement, and easier to reproduce. Furthermore, it allows new and more complex ideas to be explored and their viability to be assessed before real-world experiments, which would be expensive and time-consuming, can be implemented. One such scenario could be the utilization of multi-illumination to see its effects on the limits of human color perception, which would be difficult to implement in real-world environments.

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RADNI OKVIR ZA RAČUNALNU SIMULACIJU EKSPERIMENATA VEZANIH UZ POSTOJANOST BOJA

Sažetak

Postojanost boje je važno svojstvo ljudskog vizualnog sustava, jer nam omogućuje razlikovanje boja objekata neovisno o boji svjetlosti koja ih osvjetljava. Eksperimentalna postojanost boje dugo je proučavana tema u području ljudske percepcije. Sa razvojem moderne tehnologije i povećanjem računalne snage, kao i preciznijom tehnologijom prikaza, pružila se prilika za računalnu simulaciju eksperimenata o konstanti boje, umjesto oslanjanja na fizičke objekte poput papira. Mnogi su eksperimenti provedeni na svojstvima ljudskog vizualnog sustava u vezi s konstantom boje, od kojih su mnogi provedeni korištenjem simuliranih podražaja. Međutim, mnogi su eksperimenti zahtijevali upotrebu specijalizirane opreme ili posebnih uvjeta promatranja. U ovom radu predlažemo novi okvir za računalnu simulaciju eksperimenata vezanih uz boju HVS-a namijenjenih istraživanju svojstava vezanih uz postojanost boje ljudskog vizualnog sustava. Predloženi okvir sastoji se od softvera za simulaciju fizičkih svojstava osvjetljenja i objekata, softvera za jednostavno stvaranje eksperimenata i skupa najboljih praksi za kalibraciju računalnih monitora. Prednosti okvira u odnosu na korištenje fizičkih objekata su: niska računalna složenost, mogućnost generiranja neograničenog broja ispitnih slika, mogućnost provođenja eksperimenata na daljinu, veća fleksibilnost za vremenski ograničenu prezentaciju testne slike te niži troškovi. Okvir je testiran na dva simulirana eksperimenta. Prvi eksperiment testira osjetljivost ljudskog vizualnog sustava na promjene boje osvjetljenja korištenjem simuliranih Mondrian uzoraka. Drugi eksperiment testira granice postojanosti boje ljudskog vizualnog sustava u visoko kromatskim uvjetima korištenjem boja koje se podudaraju na simuliranim uzorcima. U prvom eksperimentu provedeno je 1800 usporedbi uzoraka boje, što je pokazalo osjetljivost na promjenu boje od 2,46°, što je usporedivo s rasponom od 2°-3° izmjerenim u drugim objavljenim radovima. U drugom eksperimentu provedeno je ukupno 3000 podudaranja uzoraka boje, što je rezultiralo s 54% točnih podudaranja. Eksperimentalna validacija pokazuje da su eksperimenti provedeni korištenjem predloženog okvira za testiranje postojanosti boje usporedivi s eksperimentima provedenima korištenjem fizičkih objekata poput obojanih papira. Stoga zaključujemo da se predloženi okvir može koristiti za razne eksperimente vezane uz boje koji zahtijevaju procjenu ljudskih sudionika usmjerenih na istraživanje svojstava ljudskog vizualnog sustava i percepcije boje.

Ključne riječi: postojanost boja; ljudski vizualni sustav; simulacija eksperimenata; podudaranje boja.

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