A test on color discrimination in complex scenes for a better comprehension of color blindness

Sofia Scipioni[1], Chiara Andrea Lombardi[1], Luca Giuliani[1], Andrea Mazzoni[2], Roberta Marcucci[2], Alice Plutino[1] and Alessandro Rizzi[1]

[1]MIPS Lab, Computer Science Department, University of Milan, Milano, Italy. sofia.scipioni@studenti.unimi.it, chiaraandrea.lombardi@studenti.unimi.it, luca.giuliani@studenti.unimi.it, alice.plutino@unimi.it, alessandro.rizzi@unimi.it

[2]Istituto di Medicina Aerospaziale dell'Aeronautica Militare, Roma, Italy. mazzoniandrea@tiscali.it, roberta.marcucci@inwind.it

Corresponding author: Alice Plutino (alice.plutino@unimi.it)

ABSTRACT

Today, in color vision and physiology, it is well known that the phenomenon of light transduction, operated by the retinal photoreceptors, cannot fully describe color perception. Color perception, in fact, is a complex phenomenon which involves not only the signal transduction in the human retina, but also the signal elaboration made by the visual cortex. For this reason, it is fundamental to consider color perception as a result of the interaction of all the colors, shapes, shadows and lights in a scene, thus of the scene spatial arrangement. In this work, we present the results of a preliminary experiment to investigate chromatic perception phenomena in spatial contexts. To perform this test, we selected five famous paintings and we asked to color blind (CB) and non-color blind (NCB) people to complete three tasks. In the first and second test, the paintings presented a missing piece. Here, the CB and NCB users had to select the correct paint missing piece among four patches with different chromatic values, at first isolated from the painting and then added in the artwork. In the third test the users had to identify the original artwork among a set of four images of the paint fully chromatically modified. Thanks to this experiment it has been possible to have a first preliminary evaluation on the role of the spatial context in color discrimination, and it has been possible to analyze some of the main limits in color blindness actual models.

KEYWORDS (color blindness, perception, visual system)

RECEIVED 11/08/2021; **REVISED** 01/10/2021; **ACCEPTED** 03/11/2021

1. Introduction

The phenomenon of vision is a complex process, and it is still not completely understood despite years of studies and modelling (Levin, et al., 2011). In the human eye, the retina is the sensible layer in which the nervous signals are generated in response to the visual stimuli coming from the surrounding environment. In the retina, the image of the visual world is focused and converted in electrical neural impulses, which are sent to the brain. The retina consists of several layers of neurons interconnected by synapses, and it is supported by an outer layer of pigmented epithelial cells. The primary light-sensing cells in the retina are the photo-receptor cells, which are of two types: rods and cones (Davson, 1990). The external part of photoreceptors is composed by a layer containing the photopigment, a chemical substance that isomerizes when absorbs light (Sharpe, et al., 1999). From this, the electric signal is generated as the first neural response to the visual stimuli, it is transmitted through the retina neural networks and it is processed by the visual cortex (Curcio, et al., 1990).

In this process of signal transduction and elaboration, the cones are the photoreceptors responsible for the photopic vision (e.g., daily vision) and for the ability to see colors. There are three kinds of cones, and each type contains a different pigment that absorbs in different percentage the radiations of the visible spectrum, and each cone contains just one of those pigments. Due to this, the cones can be classified in: Cones L that cover the region of long and medium wavelengths with a maximum at 560 nm; Cones M that absorb medium wavelengths with a maximum at 530 nm and Cones S that absorb shot wavelength with a maximum at 420 nm (Osterberg, 1935).

Color blindness (or color vision deficiency) is the decreased ability to see and distinguish colors. It is generally an inherited problem which affects the development of one or more type of cone cells. Color blindness affects mainly the male population (Nathan, 1999) and correlates also with the ethnicity (Brown & Lindsey, 2004). In general, in individuals of Northern European ancestry, the common form of red-green color blindness affects the 8% of men and just the 0.5% of women (Deeb, 2005). Color blindness can be divided in many categories, among them we focused on dichromacy (i.e., the state of having just two types of cones) and anomalous trichromacy (i.e., the state of having one of the three types of cones which behaves like one of the other two). Considering this subdivision, the kind of dichromacy or anomalous trichromacy can be classified depending on the absent (or anomalous) cone type in: protanopia (or protanomaly), deuteranopia (or deuteranomaly) and tritanopia (or tritanomaly).

Nowadays color blindness is studied and diagnosed mainly considering the retinal level of the visual path, because the problem originates from retinal anomalies. The many different color blindness tests, like the Pseudo-Isochromatic Plates (e.g., Ishihara test), the Nagel's anomaloscope, the CAD test, which have been found successful to diagnose this condition (Evans, et al., 2021), are all based on the retinal modelling of the color stimulus. However, this approach only considers the point-wise color formation, without any spatial mechanism. From the first experiments carried out by Von Helmholtz in the 19th Century and by Land (Land, 1959), (Land & McCann, 1971), Hubel (Hubel, 1995) and Wiesel (Hubel & Wiesel, 1998) in the 20th Century, it become clear that describing color vision processes as a mere transduction at retinal level of a point-wise stimulus, is not sufficient (Rizzi, 2021). Thus, current state of the art suggests color perception in carried out both at retinal and cortical level, since spatial mechanisms are a fundamental part of the robustness of our visual system and are at the base of its capabilities of adapting to widely varying visual conditions (McCann & Rizzi, 2011).

In this context, a recent series of preliminary studies investigated the role of spatial mechanisms in CB people, to assess how much the spatial arrangement affects color perception (Rizzi, et al., 2014, reprinted in Vol. 13, July 2015.), (Bonanomi, et al., 2017), (Eschbach & Nussbaum, 2021). This work follows the encouraging results evidenced by those recent studies and aims at preliminary analysis the roles of spatial arrangement and complex contexts in color perception of CB people.

Differently from other experiments, in this work, we used as test images five paintings from different periods, and we aimed at assessing how much the scene spatial arrangement of non-natural scenes may affect the color vision in NCB and CB people, considering the presence of edges and gradients in the scene. Thus, the main research question of this work is: Gradients and edges in a scene, can help CB people in identifying colors?

In this preliminary study we tested 30 subjects, of which 15 are Color Blind (CB), without focusing on the specific type of color deficiency. To this aim, in Section 2 a description of the experimental setup will be reported, explaining the three different perceptual experiments. Then, in in Section 3 we report the main experimental results, which are broadly discussed in Section 4.

2. Experimental setup

The experiment has been performed on 30 subjects, 15 CB and 15 NCB. The sample of CB people was composed by 13 males and 2 females, and the sample of NCB subjects was composed by 4 males and 11 females. In both groups the average age was of 23 years old. In order to test a wide set of subjects, the test has been performed remotely on different devices such as tablets, computers, or smartphones, and all the tests have been performed anonymously. The test has been conducted using the web application Google Form (Google, 2021). Before the beginning of the test, we made a short survey asking to the participants for sex, age, and potential color blindness, we did not focus on the type of color blindness. In fact, since it was not possible to clinically diagnose the kind of color blindness which affected the users, in the initial form we just asked to the subjects if they know to be CB. In order to confirm the hypothesis of color blindness, in the analysis of the results, we also evaluated the number of correct and wrong answers given by the single subjects, to exclude false positives.

For the experiment we selected the images of 5 paintings (see Tab. 1). This decision has been made at first to have a set of images which could be pleasant for the users, but also controlled in terms of gamut mapping. In fact, the selected paintings have been studied to have unsaturated colors thus, to be reproducible without high gamut compression by different devices. Furthermore, the use of paintings allowed us to use in the same test images very similar to the real world (Picture A - Basket of fruit, Picture B – The Tempest and Picture C - The kiss), but also images with unnatural colors (Picture D – Arearea and Picture E – Sunflowers). Thanks to this we had the possibility to evaluate if the effect of gradients and edges on color vision is present independently by the image content, the saturation or the reliability of colors.

In order to test the color discrimination of the users we altered the colors of the paintings simulating different kind of color blindness. The images have been daltonized using two different software Coblis (Colblindor, 2006-2021) and ImageJ (ImageJ, 2021). In Fig. 1 is reported an example of CIExy chromaticity shift of 10 random pixels of Picture E.

Since performing a remote test, it was not possible to assess and verify the type of color blindness of the users, we simulated the three main kinds of color deficiency to daltonize the images, to include all the possible color alterations. Nevertheless this, in this study we do not aim at testing the efficiency of the color-blind simulation but at verifying if a CB person can identify (thanks to gradients and edges) color shifts in chromaticity regions which should be perceived as uniform following the actual CB theories.

In this perceptual test we presented to the subject 4 images, the original, and 3 daltonized versions which simulate deuteranopia, protanopia and tritanopia. In order to assess the contribution of edges and gradients in the color perception we defined three different setups which correspond to three different tests. In the first test, we presented to the subject a paint with a missing piece (see Fig. 2) and the user had to select which piece is the right one, among a set of four daltonized patches (Colblindor, 2006-2021). In this first setup the missing piece must be chosen out of context.

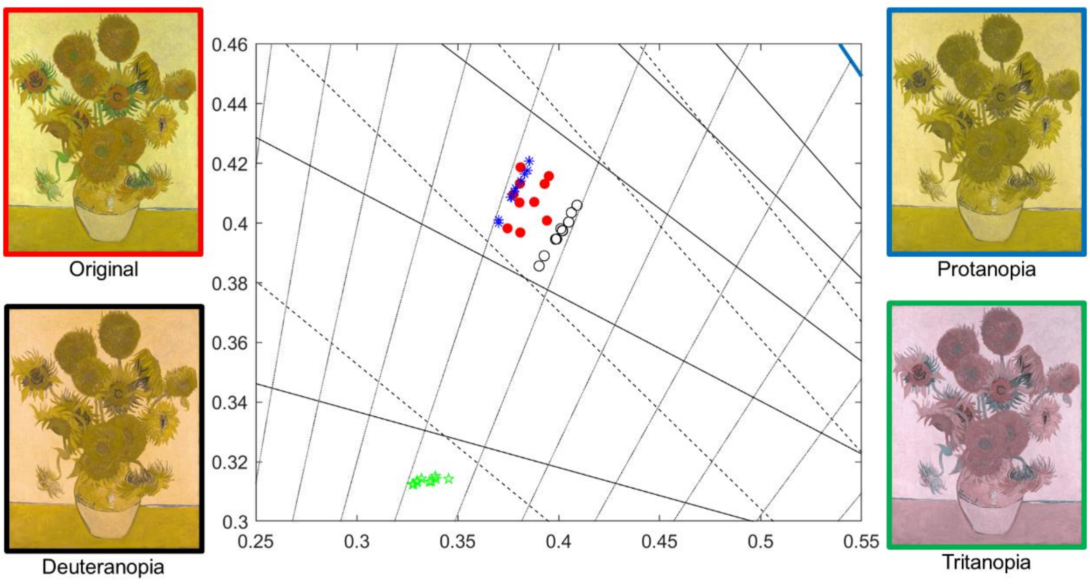

Fig. 1. Example chromaticity shift (CIExy) introduced on Picture E. The filled red dot represents some pixels of the original painting, the black circles the pixels of the deuteranopia simulation, the blue asterisks the protanopia and the green stars the tritanopia. In the chromaticity diagram, are represented also the deuteranopia (solid lines), protanopia (dashed lines) and tritanopia (dotted lines) confusion lines (Judd, 1945).

Picture ID	Description	Artwork
Picture A	Caravaggio, *Basket of fruit*; c. 1596; oil on canvas; 46x64,5 cm. Milan, Pinacoteca Ambrosiana	
Picture B	Giorgione, *The tempest*; 1507-1510; oil on canvas; 82x73 cm. Venice, Gallerie dell'Accademia	
Picture C	Francesco Hayez, *The kiss*; 1859; oil on canvas; 1,10x0,88 m. Milan, Pinacoteca di Brera	
Picture D	Paul Gauguin, *Arearea*; 1892; oil on canvas; 75x94 cm. Paris, Musée d'Orsay	
Picture E	Vincent van Gogh, *Sunflowers*; 1888; oil on canvas; 92,1x73 cm. London, National Gallery	

Tab. 1. Picture ID, description and image of the paintings used in the experiment.

 DOI: 10.23738/CCSJ.130209b

Then, in the second test we presented to the subject four versions of the original painting, completed with the patches presented before (one original and three daltonized) (see Fig. 3) and the subject had to choose which version of the painting is the correct one. In this second setup the missing piece must be chosen inside the image context. This setup has been made to create regular and irregular edges between the overall painting and the patches with altered colors. Thanks to this test we aim at assessing if a wrong-colored image piece placed inside the original paint, is more distinguishable thanks to the presence of edges.

In conclusion, as last test, the subject had to choose again which versions of the painting is the original one, choosing from four version of the painting, one original and three fully daltonized (ImageJ, 2021) (see Fig. 4). In this case, the user had the possibility to compare the paintings under analysis with the previous versions. Thus, in this last setup, we aim at assessing the ability of CB users to identify the overall color of the image, resorting to comparisons.

For all the three tests composing the experiment, we gave to the subject the possibility to select one answer or the option N/D (Non-Defined), when he/she could not perceive any difference among the answers. In the Appendix A are reported all the test images for all the five analyzed paintings.

3. Results

In Fig. 5, 6 and 7 are reported the answers given by the CB and NCB users, divided per painting.

Considering the results of the first test (Fig. 5), the answers are strongly coherent in the first group (NCB) and presents a greater variability in the CB group. For the paintings B, C and D, the majority of the CB answers are exactly like the NCB's, especially in the case of the paint D. For what concerns the paints A and E, just few CB answer correctly, thus there is an increase of variance. For the paintings A and E, 6 people out of 15 answered with N/D.

Also in the second test, the NCB provided quite uniform answers (Fig. 6), but an increase of variance can be observed in the NCB and in the CB answers. Some N/D answers have been reported by the NCB subjects for the paintings D and E, in particular the painting E is the one which presents the majority of N/D answers for both CB and NCB. This painting is the one in which the CB subjects make more mistakes. Considering the CB answers, the visualization of the daltonized patch inside the painting (Test 2) made more difficult the identification of the correct patch, especially for the paint D, where in the first test the CB gave 12 correct answers.

Fig. 2. First test example (picture A).

Fig. 3. Second test example (picture A).

Fig. 4. Third test example (picture A).

Considering, now, the subdivision of the answers per users (Fig. 8 and 9), this analysis could be useful to identify CB people in the NCB group, or vice versa. For what concerns the CB test group (see Fig. 9), 5 subjects out of 15 made more than 4 errors and 11 subjects out of 15 gave N/D answers. A particular trend can be noted for subject 7, who gave the biggest number of wrong answers (13) never choosing the N/D option and for subject 6, who gave 13 correct answers out of 15 (like some NCB people). These results will be discussed in the next Section.

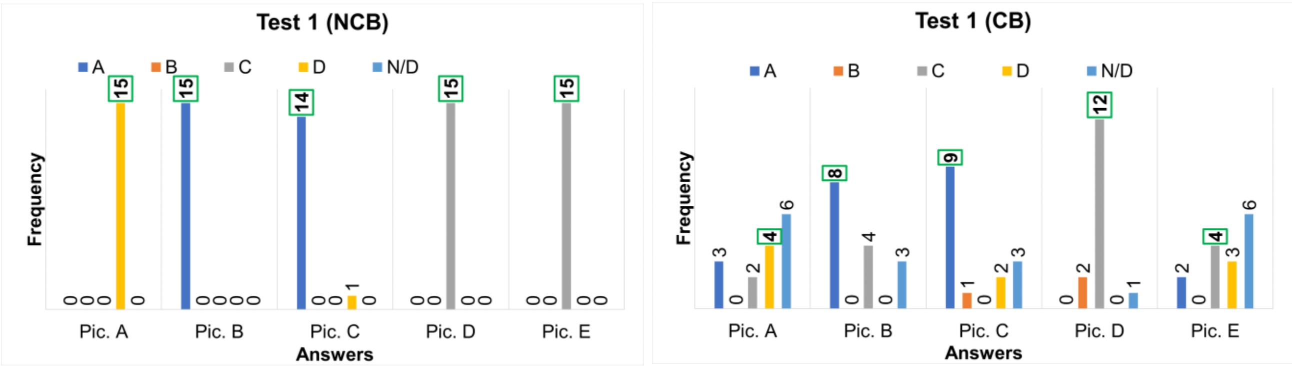

Fig. 5. Comparison of the answers given in Test 1 by NCB and CB subjects. The correct answers are evidenced in green. In these plots it can be noticed that Pic. D is the one which causes less error in CB people, while Pic. A and Pic. E causes the biggest error and variance in the answers.

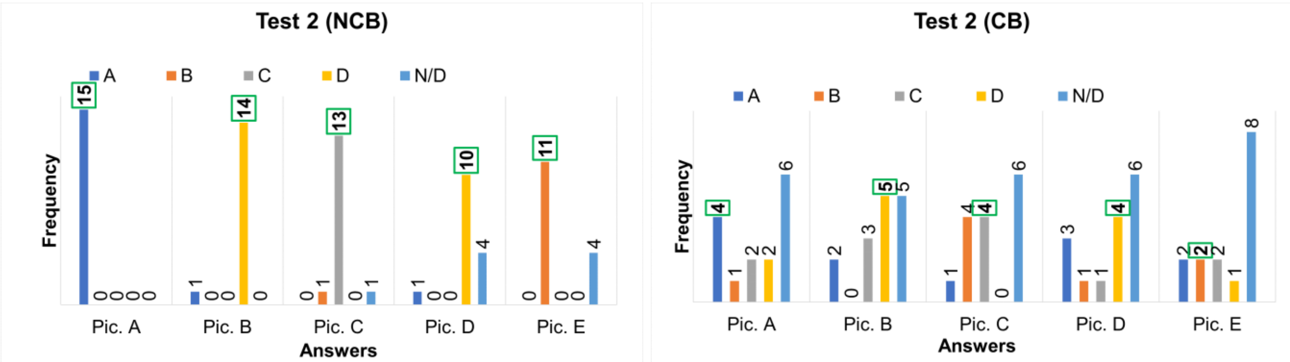

Fig. 6. Comparison of the answers given in test 2 by NCB and CB. The correct answers are evidenced in green. In these plots the Pic. D in NCB presents the lowest value of correct answer. In CB subjects the answer variance is high and Pic. E causes the lowest value of correct answers.

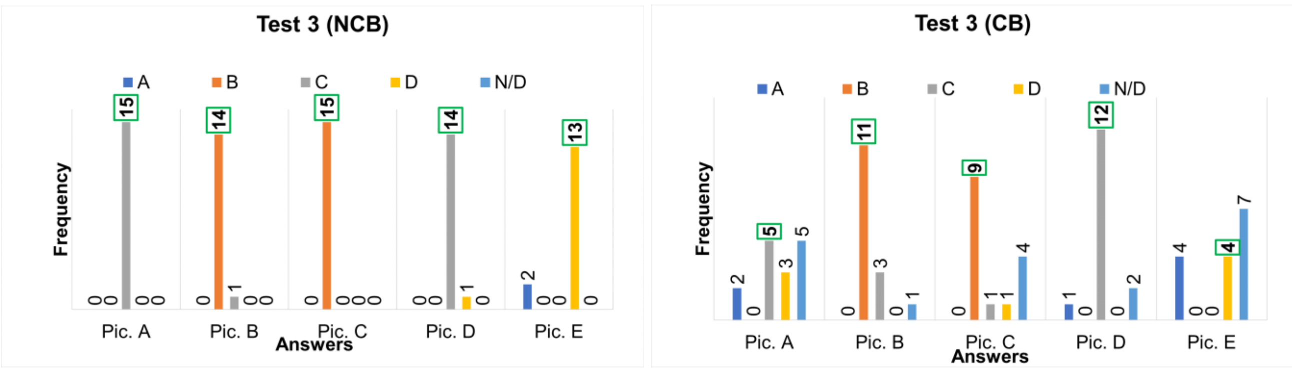

Fig. 7. Comparison of the answers given in test 3 by NCB and CB. The correct answers are evidenced in green. This is the test in which CB people perform better, especially for Pic. B and Pic. D. The images Pic. E and Pic. A produce high error also in this case.

4. Discussion

In general, the NCB test group had no problems in answering to the tests, even if some error (maximum value of 2) is present and some answers are N/D.

In Test 1, the users had to guess the right image missing piece, out of context. In this task, for Picture B, C and D the majority of CB people answered correctly. This result was surprising and unexpected, especially if compared with the results of Test 2. Considering the aim of this work, this test is very significant because the daltonized patches are reported inside the painting, thus the color differences are seen inside a context with edges and gradients. This test is the one in which the variance in the answers has increased the most and the paintings D and E are the ones which cause more errors in the answers. The answers given by the CB test group are more heterogeneous and, even in this case, the second test created the biggest variance and a greater number of errors. Despite the presence of edges among colors, CB, but also some NCB people, could not see the difference between the different test images. A preliminary explanation of this result could rely in the assimilation phenomenon of the human visual system. It is clear that this phenomenon must be further studied and analyzed from the physiological, neurological, and psychological point of view, but this result demonstrates the presence of a spatial elaboration of the signal.

This is in line also with the strong decrease of errors in CB test group switching from the second test to third test.

As a consequence, if in NCB people the number of correct answers is robust and constant in the three different tests, for CB people the strong variations could suggest the presence of a spatial elaboration of the signal switching from a situation to another.

Considering now the single paintings (see Appendix A), we can generalize saying that the paints A, B and C represents subjects which have color arrangements similar to natural scenes, despite the paintings D and E which have non-natural color distribution. This fact could have led to a greater error in NCB and CB test group, especially in the second and third tests, where all the daltonized colors could be considered probable (e.g., in Picture A where an apple is colored in red, green and yellow). On the other hand, considering the setup for Test 1 and Test 3, in an abstract image like Picture D (see Figure 4A in the Appendix), the original painting is clearly distinguishable for NCB as well as for CB people. This happens also for Picture B, which is more similar to a real image, even if in Test 1 the number of error and N/D answers is still high.

Considering the single subject analysis, and in particular the CB test group, the subjects can easily be divided in two groups. On one side we have the subjects who gave more than half wrong or N/D answers (subjects 1, 2, 3, 5, 7, 8

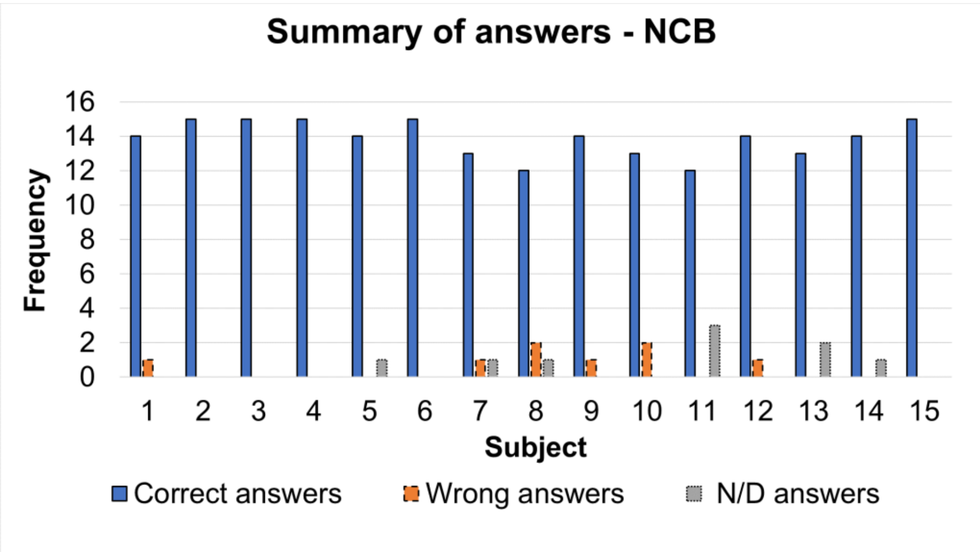

Fig. 8. Summary of answers given by the fifteen NCB subjects.

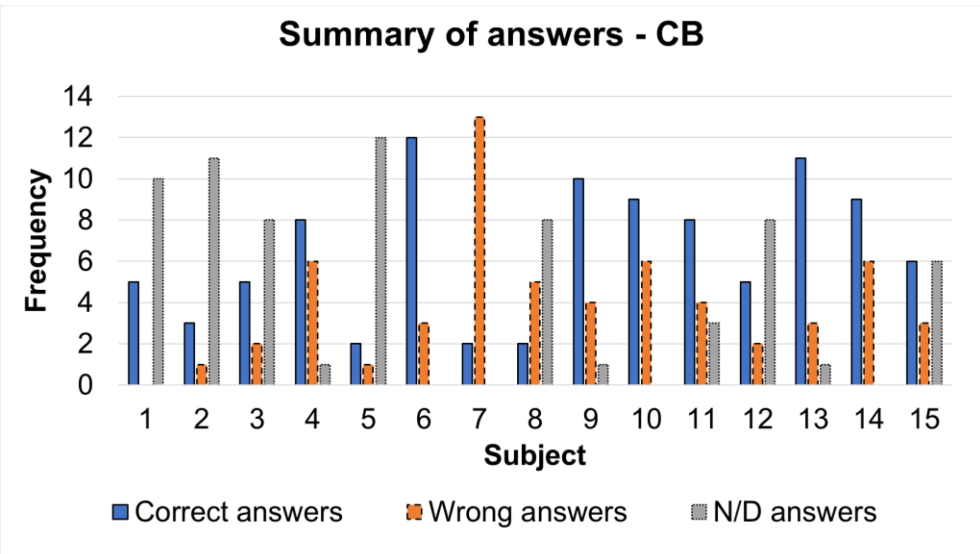

Fig. 9. Summary of answers given by the fifteen CB subjects.

 DOI: 10.23738/CCSJ.130209b

and 12) and, on the other side, the subjects who gave more than half correct answers (subjects 4, 6, 9, 10, 11, 13, 14 and 15). From this analysis it is clear that all the CB people, who clearly do not perform as well as the NCB test group, can have not only different types of color vision deficiencies, but also different severity levels. Clearly, also this point should be better analyzed and studied. In addition, as future work, further analysis both in remote and in laboratory conditions should be made, in order to evaluate not only the role of spatial arrangement intended as color distribution in the image, but also the role of different monitor qualities and sizes, and observing conditions in the assessment of color.

5. Conclusion

Color perception is a complex phenomenon which involves not only the signal transduction in the human retina, but also the signal elaboration made by the visual cortex. Color blindness is mainly modeled and studied at the retinal level, since it is an inherited problem which affects the development of one or more type of cone cells. In order to overcome the retinal level in color blindness study and analyze the role of edges and gradients in color vision, we performed three color perception tests. Aim of this study is to assess if the spatial arrangement in which colors are inserted may increase the ability to discriminate colors in CB people.

This was a preliminary study, and further studies and analysis from the physiological, neurological, and psychological point of view are needed, but this experiment has been useful to suggest that the integration of spatial arrangements in models of vision is mandatory, as well as in color blindness diagnosis tests.

This trend has been demonstrated by the test results, but also by the analysis of the single subjects' answers, which show that color deficiency presents different levels of severity. This specific analysis aims to be a further small preliminary step in the direction of rising the awareness of the scientific and medical community on the necessity of developing new methods and techniques able to diagnose not only the presence/absence of color blindness, but also at evaluating and measuring the severity level in real context and not just on isolated patches, not representative of real working tasks

In conclusion, with this preliminary experiment we aim at exploring the boundaries of the actual knowledge about color vision deficiency, evidencing that this phenomenon cannot be studied just at the retinal level but must also consider the visual spatial mechanisms.

6. Aknowledgement

The experiments presented in this paper have been made thanks to the collaboration between the Department of Computer Science of Università degli Studi di Milano, with the Istituto di Medicina Aerospaziale of Rome as part of the CORISAMIL project Screening del daltonismo in profili operativi complessi del volo militare: studio e analisi di nuove metodologie di diagnostica alternativa.

7. Conflict of Interest

The authors declare no conflict of interest.

8. Declaration of funding sources

The authors received no specific funding for this work.

9. Short biography of the authors

Sofia Scipioni – She is a student of "Cultural heritage conservation science" at Università degli Studi di Milano. She graduated in "Science and Technology for Studying and Preserving the Cultural Heritage and Information Storage Media" and now her interests and studies are focused on the different way of materials deterioration connected with cultural heritage.

Chiara Andrea Lombardi – She graduated in 2019 in "Science and Technology for Studying and Preserving the Cultural Heritage and Information Storage Media" at the University of Milan with a thesis dealing with the identification of pigments through analytical investigations on Roman wall painting fragments. She is currently obtaining her master's degree course in "Cultural heritage conservation science" at the University of Milan.

Luca Giuliani – He is a master degree student in Computer Science. He obtained his bachelor degree with a thesis concerning a simple implementation of a space variant model for the retinal-cortex vision. Currently he is focusing on distributed systems and IoT devices which could be applied to study human visual perception.

Andrea Mazzoni – Ophthalmologist MD, PhD, Italian Air Force Medical Officer serving at the Aerospace Medicine Institute in Rome. His main task is military and civilian airworthiness. Specialized in clinical and instrumental diagnosis, mostly in anterior segment of the eye. He has been dealing with human visual system perception of colors in a long time. He is currently the head of the research study: "Screening of color blindness in complex operational profiles of military flight: study and analysis of new alternative diagnostic methodologies" collaborating with UNIMI, the University of Milan.

Roberta Marcucci – Ophthalmologist MD, Italian Air Force Medical Officer at Aerospace Medicine Institute in Rome. Her clinical field of application is aviation medicine and the assessment of medical fitness of military and civilian aviation personnel, according to their special duty status. Her professional background includes medical retina, cornea, refractive surgery.

Alice Plutino – She recently obtained a PhD in Computer Science at Università degli Studi di Milano. Her research interests are: Color Science, Colorimetry, Image Enhancement, Image Digitization and Archiving, with a particular interest in Cultural Heritage applications. She is author of a book on film restoration and of several journal and conference papers of national and international relevance.

Alessandro Rizzi – He is Full Professor at the Department of Computer Science at the University of Milano. He is doing research since 1990 in the field of digital imaging with a particular interest on color, visualization, photography, HDR, VR and on the perceptual issues related to digital imaging, interfaces, and lighting. He is member of several program committees of conferences related to color and digital imaging, and author of about 400 scientific works.

References

Bonanomi, C. et al., 2017. An App-based Assessment of SiChaRDa, an Image Enhancer for Color-Blind People. *Journal of Imaging Science and Technology*, Volume 61, Number 4,, pp. 40405-1-40405-9.

Brown, A. & Lindsey, D., 2004. Color and language: worldwide distribution of daltonism and distinct words for blue. *Visual Neuroscience* 21, pp. 409–412.

Colblindor, 2006-2021. Coblis — Color Blindness Simulator. [Online] Available at: https://www.color-blindness.com/coblis-color-blindness-simulator/ (Accessed: 30 August 2021).

Curcio, C. A., Sloan, K. R., Kalina, R. E. & Hendrickson, A. E., 1990. Human photoreceptor topography. *Journal of Comparative Neurology*, vol. 292 (4), pp. 497–523.

Davson, H., 1990. *Physiology of the Eye*. s.l.: Macmillan International Higher Education.

Deeb, S. S., 2005. *The molecular basis of variation in human color vision*. Clinical genetics 67.5, pp. pp: 369-377.

Eschbach, R. & Nussbaum, P., 2021. Examining spatial attributes of color deficient observers. *IS&T Electronic Imaging*, 18-28 January 2021, pp. Online.

Evans, B. E., Rodriguez-Carmona, M. & Barbur, J. L., 2021. Color vision assessment-1: Visual signals that affect the results of the Farnsworth D-15 test. *Color Research & Application* , Volume 46.1 , pp. 7-20.

Google, 2021. Google Forms. [Online] Available at: https://www.google.com/forms/about/ (Accessed: 12 September 2021).

Hubel, D. H., 1995. Eye, brain, and vision. s.l.:*Scientific American Library/Scientific American Books*.

Hubel, D. H. & Wiesel, T. N., 1998. Early exploration of the visual cortex.. *Neuron* , Volume 20.3, pp. 401-412.

ImageJ, 2021. Download. [Online] Available at: https://imagej.nih.gov/ij/download.html (Accessed: 12 September 2021).

Judd, D. B., 1945 . Standard response functions for protanopic and deuteranopic vision. *Journal of the Optical Society of America (JOSA)*, Volume 35.3 , pp. 199-221.

Land, E. H., 1959. Experiments in color vision. *Scientific American*, Volume 200.5 , pp. 84-99.

Land, E. & McCann, J., 1971. Lightness and retinex theory. *Journal of the Optical Society of America (JOSA)*, pp. 1–11.

Levin, L. A., Kaufman, P. L. & Alm, A., 2011. *Adler's Physiology of the Eye*. s.l.:s.n.

McCann, J. J. & Rizzi, A., 2011. *The Art and Science of HDR Imaging*. s.l.:John Wiley.

Nathan, J., 1999. The evolution and physiology of human color vision: insights from molecular genetic studies of visual pigments. *Neuron* 24, pp. 299-312.

Osterberg, G., 1935. Topography of the layer of rods and cones in the human retina. s.l.:*Acta Ophthalmol*.

Rizzi, A., 2021. Colour after colorimetry. *Coloration Technology*, Volume 137, pp. 22 - 28.

Rizzi, A., Eschbach, R., Quaranta, A. & Bonanomi, C., 2014, reprinted in Vol. 13, July 2015. Modified Ishihara test to study the role of edges in color discrimination. *Italian Journal of Aerospace Medicine*, Vol.11 .

Sharpe, L. T., Stockman, A., Jägle, H. & Nathans, J., 1999. *Opsin genes, cone photopigments, color vision, and color blindness*. Cambridge University Press, pp. 3–5.

Appendix A

Fig.1A. First, second and third tests for the picture A (Caravaggio, Basket of fruit).

Fig.2A. First, second and third tests for the picture B (Giorgione, The tempest).

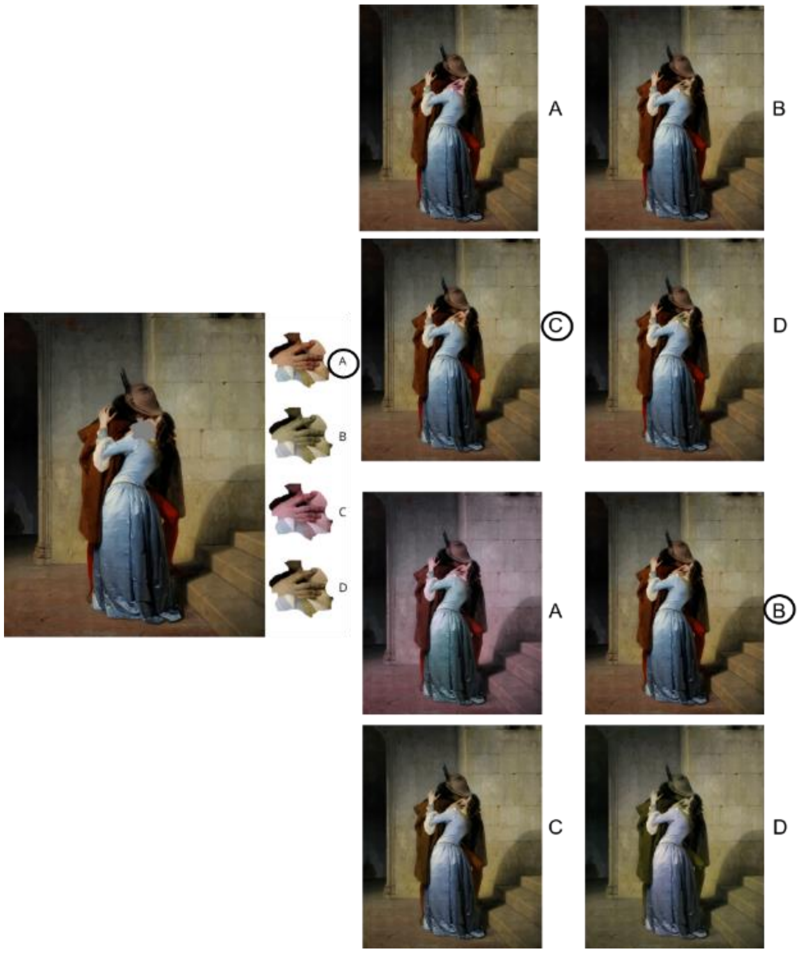

Fig.3A. First, second and third tests for the picture C (Hayez, The kiss).

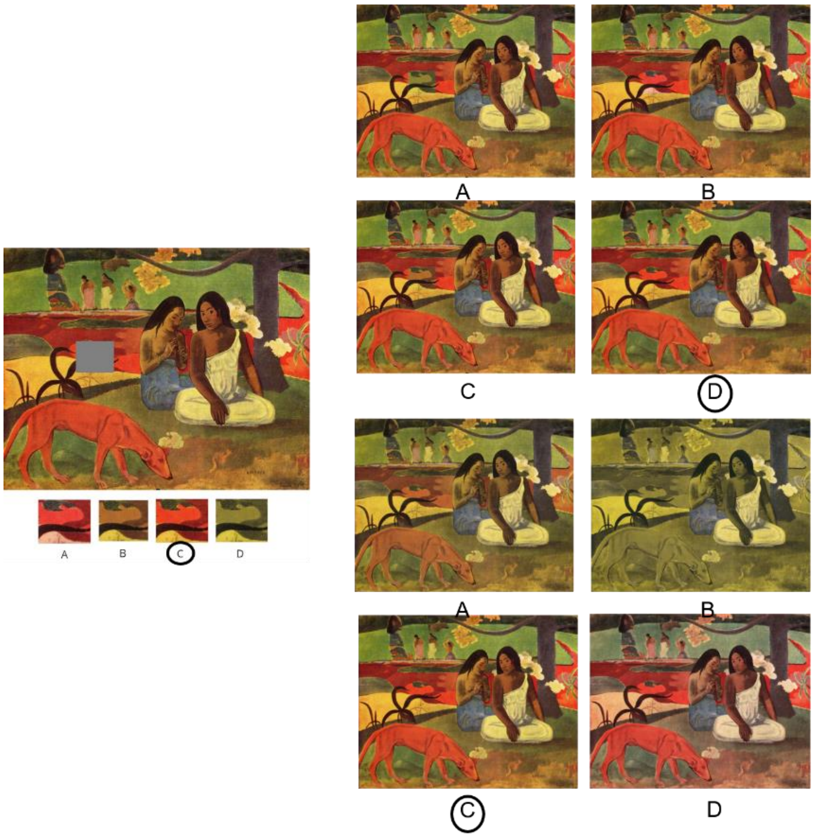

Fig.4A. First, second and third tests for the picture D (Gauguin, Arearea).

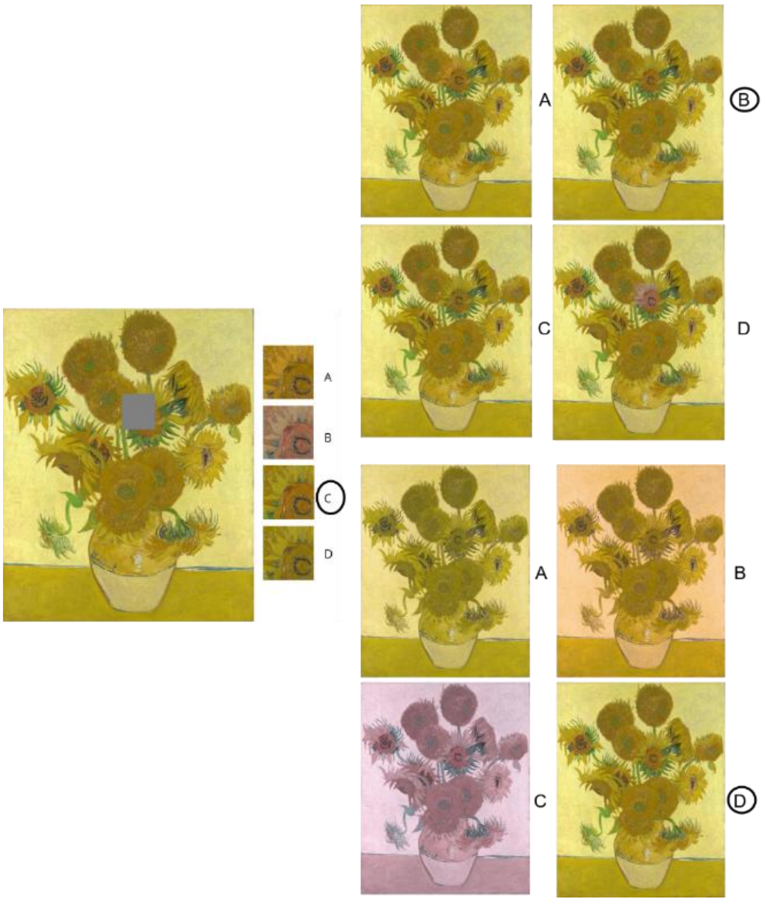

Fig.5A. First, second and third tests for the picture E (Van Gogh, Sunflowers).