Received: 28 May 2020 | Revised: 7 July 2020 | Accepted: 5 September 2020
DOI: 10.1111/cote.12494

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Coloration Technology

ORIGINAL ARTICLE

How colour-deficient observers see things, or not.

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Abstract
Colour deficiency or, colloquially, colour blindness, is common and has been observed and described in the scientific literature for *ca*. 200 years. In more recent times, algorithms have been developed that simulate the effect of colour deficiency to a colour-normal observer. Sometimes these algorithms are used to indicate potential problems in the colour design, but often the implicit assumption is that a colour-deficient observer actually sees things that way. But do they? This paper questions some of the underlying assumptions of the algorithms.

1 | INTRODUCTION

Colour deficiency (or colour blindness) is a common condition afflicting *ca*. 8% of males and a smaller percentage of females. A good overview can be found in references 1 and 2, including the underlying genetics and variations across different populations. There are several types of colour deficiency, and when talking about colour-deficient observers (CDOs), one has to remember that for final assessments, the exact nature has to be specified. However, for the purpose of this paper, it is sufficient to use broad terms because we will be looking at some of the underlying assumptions are used in the algorithms. In many cases, it is also understood that the assumption might not go into the algorithm directly, but rather into the interpretation of the algorithmic results.

This paper describes some experiences with CDOs as they relate to real-life experience and performance. Individually and as a group, the examples given will pose questions that are not well addressed in current descriptions of colour deficiency.

2 | MEASURING COLOUR DEFICIENCY

There are many ways to identify CDOs. The most common ones are the Ishihara test and the more extensive Farnsworth test. These tests are described in detail in references 1 and 2 and a list of other methods can also be found elsewhere.[3]

2.1 | Why do we need a colour deficiency test?

An individual who is not able to distinguish red from green should know that they have a problem, for instance, when they try to cross a road and are run over by a car. But at what age does a person actually realise that they are colour blind? Judging from the algorithms and descriptions given, this ideally should occur early in life, at some point during the first few years of schooling.

Heowever, here are some real-world examples:

- During a military draft examination, an 18-year-old male discovers that he cannot read the numbers presented in the Ishihara test. He has frequently crossed the road safely but did not know that he was colour-deficient. (R.E. was present at this event.)
- A man in his 50s is asked to give a talk on colour at an industrial forum and when handed the Ishihara test to use in the presentation says, “Great, I use one of those with a number inside and one without”. The one without was a standard chart for deuteranomalous colour deficiency. This

man had worked with a group of colour scientists. He had not noticed previously that he supposedly could not tell the difference between red and green traffic lights. (R.E. was present at this event.)
- A well-established senior colour scientist started a consultancy offering seminars to industrial scientists working in colour design and printing. At the beginning of each seminar, every attendant was given a colour vision test. However, this practice was stopped because of those people coming to the seminars—who were responsible for colour in their companies—approximately the same percentage as the general public failed the test. How does one tell an attendee with responsibility for colour in their company that they are colour-deficient? (Relayed by personal communication to R.E.)

Anecdotes do not necessarily prove anything, but in this situation they do raise questions about the accuracy of our description of colour deficiency.

On the other hand, these anecdotes also answer the question of why we need colour deficiency tests. If people in those age groups who are carrying out the work described do not know that they have a colour vision deficiency, then tests are definitely needed. However, the relevancy of the tests performed raises doubts about the assumptions made regarding colour deficiency. It is not as straightforward as an explanation citing a typical confusion of colours might suggest.

3 | SIMULATING A CDO

The simulation of colour deficiency is a key subject. There are several algorithms that can simulate a CDO. There are also websites that will convert a submitted image to one which a CDO would see; this usually includes an option to simulate a specific colour deficiency, which means that the images provided for protoanomalia and deuteroanomalia are different and distinct to a colour-normal observer, but appear identical to a CDO.

Note that one has to be careful to distinguish the algorithm from the way in which the algorithm is used. For example, taking a colour design and mapping it to a black and white image to ensure that the design also works for CDOs is a sensible approach to ascertain that the design has clear luminance variation and thus a high likelihood of being a good design. This approach does not claim that the CDO cannot tell the difference between the colour image and the black and white image, just that the simulation is useful within a certain range of applications.

Figure 1 shows one of these simulations for a deuteroanomalous observer. This image is often used to simulate how a CDO sees an image. For our purposes it is not important to identify the algorithm used, beyond stating that it is both well-known and frequently used. Here, we simply want to use the image to perform a thought experiment concerning the process of how one sees.

If person A only sees the image in one way (ie, as the image on the right), then this means that person A cannot distinguish between the two images. If the images appear differently to another observer, than that observer clearly does not see the image in just one way. This assertion needs to be questioned.

This can be done simply. Figure 2 shows the result of a Farnsworth test for a deuteroanomalous observer, who matches person A as per the assumptions of Figure 1. The thought experiment asks if person A can tell the difference between the left and right images of Figure 1. The answer to this is "yes". Those two images are clearly different.

At this point, it is important to state that the finding is “the images are different”. Nobody is arguing that when describing the image, person A would describe the change as something equal or similar to the way a colour-normal observer would describe it. The claim in this paper is simply that in many cases the simulated image is clearly distinguishable from the original image and thus does not correctly portray how person A sees.

From a mathematical perspective, the claim that an individual “sees” something can be described as a projection operator. The input image is projected into the visual space of the target observer. Here, “visual space” refers to the visual experience of the observer and not to a specific mathematical coordinate system. But this also means that the target observer cannot distinguish between the two, otherwise the projection would either be incomplete—missing parts of the target visual space—or incorrect. Either way, the ability to

FIGURE 1 An original image (left) and a simulation of the experience of a deuteroanomalous colour-deficient (D-type) observer (right)

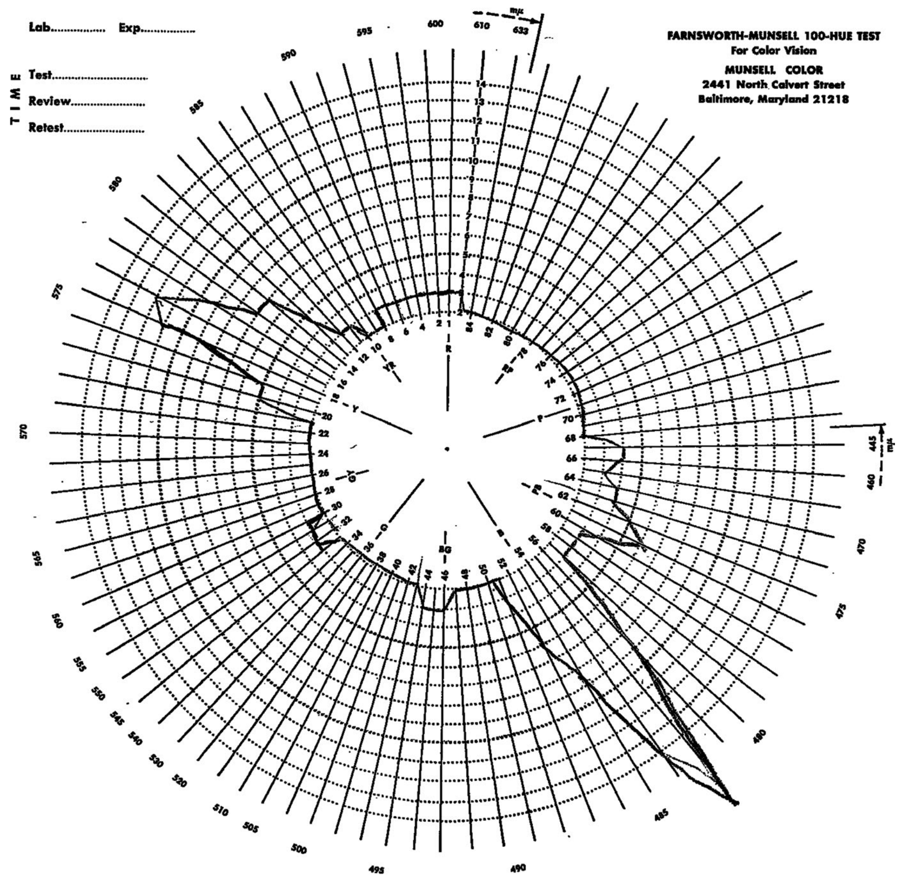

FIGURE 2 Farnsworth result for a D-type CDO. Note that this observer has a sufficiently strong derivation from colour-normal vision that the actual measured values are outside the standard Farnsworth range (in the lower right of the chart)

distinguish images after simulation indicates that the algorithms are not true "projections" into the vision of a CDO.

It is important to state that, in general, algorithms are good approximations, in the sense that the difference between an original and simulated image is sometimes difficult, and occasionally impossible, for a CDO to discern. This leads one to question the completeness of the projection and not the accuracy. In other words, for the given assumptions and boundary conditions, the algorithm appears to perform well. However, there seems to be a part of visual space that the algorithms are not incorporating, and therefore it is important to ask which properties, variables and connections are missing from our current understanding of colour vision.

4 | IMAGE PREFERENCE AND CDOS

There is no question that a CDO sees an image differently from the way a colour-normal observer sees the same image. There are many scenarios that we can create to show such differences. But looking at Figure 1, there also seems to be a set of images where the performance of deficient and normal observers becomes comparable, despite the task seemingly being a colour task.

One example of this is the topic of image preference (to contrast with a target-finding task). In order to develop a system that automatically adjusts image parameters to create a visually preferred result (https://creativepro.com/xerox-innovation-at-work-automatic-image-enhancement/), a large number of preference comparisons and observations were taken. There did not seem to be a clear distinction between the two types of observers; however, these experiments were limited to images classified as "natural" images. Additionally, all images began as suboptimal then were enhanced. This is a very different scenario to the (frequently used) approach where an image is artificially altered and algorithms are designed that invert that modification automatically. For example, image-sharpening algorithms are often developed and judged by applying them to previously blurred images. This approach allows a numerical comparison between an actual original image and one recovered from an assumed deficiency.

An interesting observation along the lines of achieving comparable "preference" from CDOs and colour-normal observers was made by Lundekvam and Green[4] for the case of colour harmony. Their images were clearly not natural images, but the intent of colour harmony is to create colour combinations that are "pleasant" to an observer. Their final conclusion was that "The results showed that the harmony judgements of these two groups were not significantly different".

These two examples from the preference domain are both anecdotes rather than well-established and replicated findings, but they point in the same direction as the colour-deficiency simulations in section 3. Are there additional dimensions to visual space that our current approaches and assumptions do not consider sufficiently?

5 | CDOS AND MUSIC

Concerning the subject of CDOs and music, I am not claiming that vision and hearing in humans are directly linked. Nor am I implying that musical choices are influenced by our colour vision. This section does, however, introduce one relationship that we rarely (if ever) explore. Both are human senses: Is there something we can learn from our knowledge of one sense and bring that into the other? In this context, we can conduct the following thought experiment:

> How many people do you know that have absolute pitch? How many people can tell tones apart that differ by a quarter tone or less? If you are reading this, think of your favourite song and say what key it is in. To an individual with perfect pitch, you might appear pitch-deficient in the same way as a CDO appears color-deficient to a colour-normal person.

But you still can enjoy the music and recognise melodies; it still "means" something.

In music, the answer seems to be obvious (although the obvious answers are the dangerous answers). It is the relationship of the notes to one another that our brains detect. Is there a similar solution for colour vision?

6 | CONCLUSIONS

The main conclusion arising from this paper is that there are more questions than answers regarding human colour vision. Clearly, the experiments with CDOs generate reproducible results and are scientifically sound. But are the conclusions based on these experiments also sound? Are our conclusions simply misguided—something that is very unlikely—or are we extending the conclusions beyond their validity? What does an experiment performed in a proper scientific setting (ie, separating variables) tell us about complex natural scenes? Under what circumstances is the eye as a sensor the main driver in vision, and under what circumstances does our brain play the major role? Is the brain simply adding a layer on top of the sensory input, or is it playing a more active role?

From a physical experimentation standpoint, this active role can be considered to be "meddling" or "illusion". An "optical illusion" is a term we often use when describing things that do not readily lend themselves to our descriptions. But if an illusion is shared by (virtually) all humans, does it not make that illusion a reality for colour vision?

7 | OUTLOOK

This leads me to look ahead: What is the current status of colour research and colour vision research? Are we close to completion, and will inserting the human brain into the equation only add a few more decimal places to our description? Or are we beginning to realise that the brain plays a more meddlesome role in colour vision?[5]

For young researchers entering this field, I would hope that we are starting to incorporate the human brain more deeply into our vision work. And my personal hope is that research in colour deficiency might be one good entrance to this.

REFERENCES

1. https://en.wikipedia.org/wiki/Color_blindness
2. https://www.color-blindness.com/
3. https://www.science.gov/topicpages/c/color+vision+test.html
4. Lundekvam S, Green P. How is colour harmony perceived by observers with a colour vision deficiency? Color Imaging XXIV, at EI2019.
5. Shock therapy improves women's colour blindness. *New Scientist*. May 23–29, 2020.

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How to cite this article: Eschbach R. How colour-deficient observers see things. *Coloration Technol.* 2020;00:1–4. https://doi.org/10.1111/cote.12494