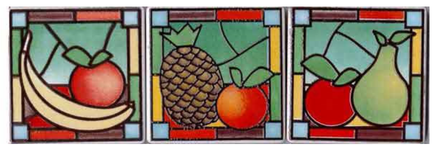
Grades 9-12

Digging Deep into Science Literacy

ACTIVITY: Color vision in humans and animals

Purpose

The normal human eye can perceive a whole rainbow of colors, yet the Sun and most light sources we are familiar with in everyday life produce light that seems to us to be white. Of course, we also see colored lights, for example in fountains, traffic lights, at dances, in theaters, etc. But does everyone see colors in the same way, and what about other animals?



In this activity, you will first explore how normal human color vision works. Then we will explore how the world would look to a person whose color vision is different? The key questions for this activity are:

1. How do normal human eyes see color?
2. What does the world look like with different color vision?

Initial Ideas

Your instructor will project red and green colored lights on a white wall (or screen). Now suppose your instructor were to move the lights so that they partially overlap on the screen.

What color do you think you would see in the region where they overlap? Why do you think so?

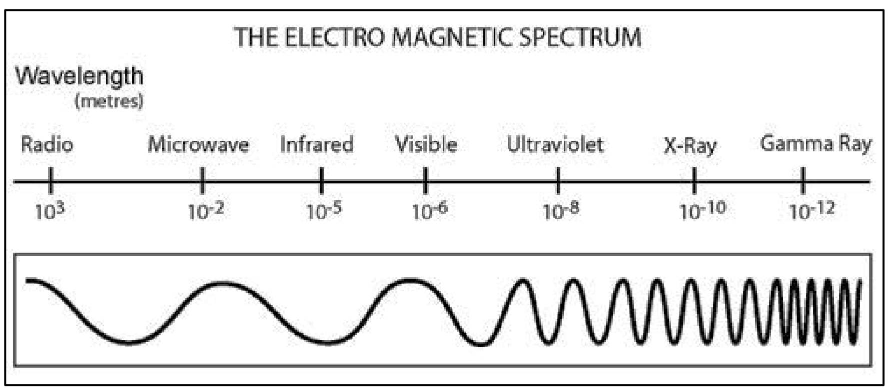
Participate in a discussion. Make a note of any ideas or reasoning that are different from yours.

Following the discussion your instructor will overlap the red and green lights.

What color do you see in the region of overlap? Is this what you predicted?

Light as an Electromagnetic Wave

As you may be aware, light is a type of wave. However, unlike other waves, light waves do not need a medium (material) to move through. Instead, when electric charges oscillate, they create disturbances in the electric and magnetic fields around them. These fields exist throughout the whole universe within all materials, and even in the vacuum of space. The disturbances created by oscillating charges move away from the source (oscillating charge) as ***electromagnetic (EM) waves***. Depending on the details of how the oscillating charges move, these EM waves can have any wavelength. Together, all the different types of EM waves form what we call *the electromagnetic spectrum*, with a continuous range of wavelengths from many meters (radio waves) to less than a trillionth of a meter (gamma-rays). What we call visible light is actually only a small part of the complete EM spectrum as shown here.



Collecting and Interpreting Evidence

Each group will need

- Envelope with three color gels (red, green, blue)
- Two flashlights with narrow beams
- Tubular bulb in socket
- Spectral glasses (one pair per person)
- Computer with internet connection (or flash drive)
- Second envelope with three different color gels (yellow, cyan, magenta)

Exploration #1: How do we see colored lights?

STEP 1. Turn on your flashlights and (if possible) focus each of them so they produce a small, bright, white spot when shone on a sheet of white paper. Now hold the red gel over one flashlight and the green gel over the other one, and shine them onto the paper so they are about the same brightness. (You may have to hold them at different distances from the paper to achieve this.)

What color do you see where the red and green lights overlap? (This should be close to the same as your instructor's demonstration.)

What color do you think you would see if you overlapped red and blue spots of light? What about blue and green?

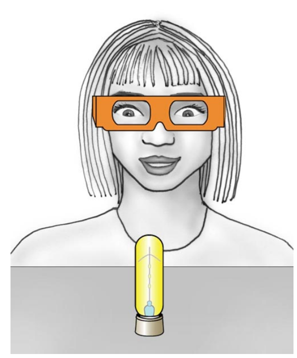
***Prediction*:**

Red + **B**lue =

Blue + **G**reen =

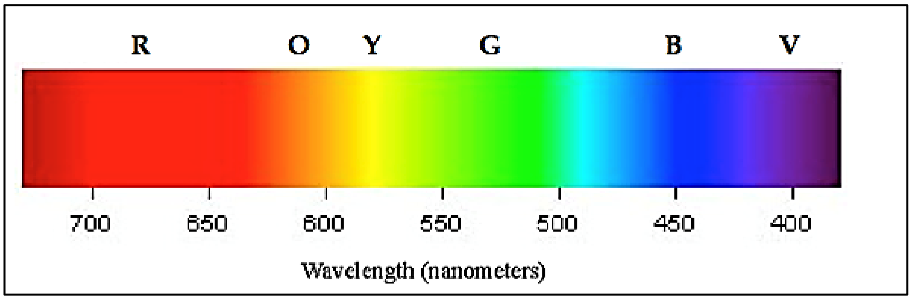
Now use the appropriate color gels to check your predictions. Do your observations match your predictions? If not, describe what colors you do see.

STEP 2. We will now try to understand these results. Plug in and turn on the light bulb. It should look something close to white in color to you. Now look at it through your *spectral* glasses. You should see many bands of colors. The range of colors that you see is called the color ***spectrum*** of the white light source. (The glasses act a like prism to create a spectrum from the white light coming from the bulb.)

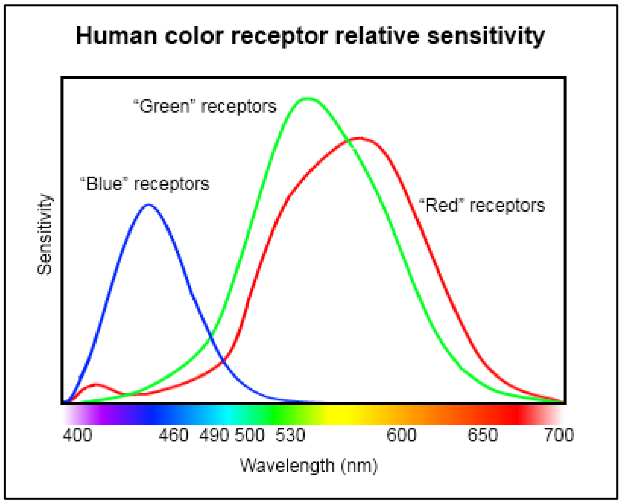


Close one eye and concentrate on the band of colors that seems to spread out to the immediate **LEFT** from the light source. You should see the familiar 'rainbow', the colors of which are sometimes simply referred to as **ROYGBV**. (Red, Orange, Yellow, Green, Blue, Violet)

You are seeing this spectrum because the human eye is sensitive to the wavelengths of the electromagnetic spectrum between about 380 nm (perceived as violet light) and 730 nm (perceived as red light). (1 nm = 1 x 10^{-9} m.)

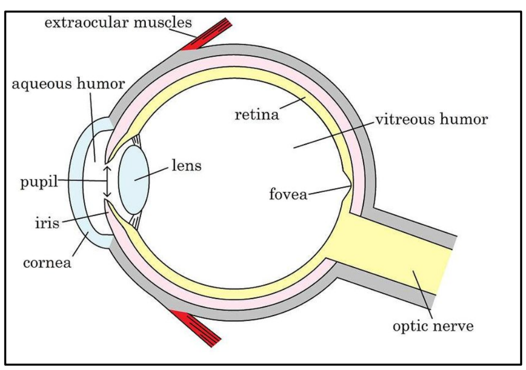


A normal human eye has three different types of color sensitive receptors (called '*cones*') in it that are sensitive to different regions of this color spectrum, as shown in the graph to the right.

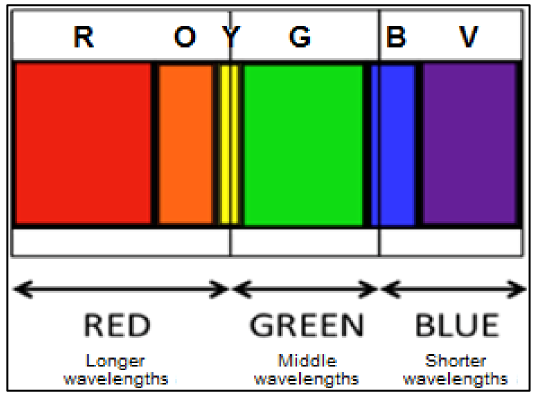


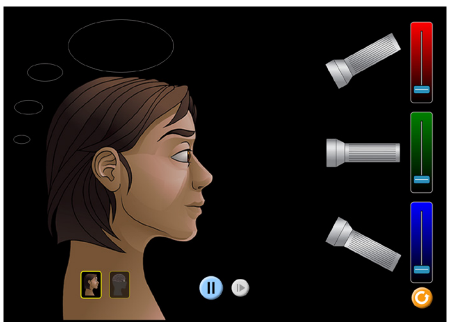
One type is most sensitive to colors that lie toward the **red** end of the spectrum. We will call these **R** *receptors*. A second type is most sensitive to the middle regions of the spectrum (**G** *receptors*). The third type is most sensitive to the blue end of the spectrum (**B** *receptors*).

These color receptors (cones) are concentrated in the *fovea*, a small pit in the central area of the retina. This is the small area where light is focused when you are looking directly at an object. (Another type of light receptor (called *rods*) is more widely distributed across the retina with none in the fovea itself. Rods do not detect color but are much more sensitive to light, thus helping us see in low light conditions - but only in shades of light and dark.



As can be seen from the graph of sensitivity of color receptors, there is significant overlap of these regions of sensitivity. However, for ease of discussion it is convenient to divide the entire color spectrum into three broad bands, corresponding to the ranges over which each type of receptor is the most sensitive. We will call these bands red (**R**), green (**G**) and blue (**B**), as shown here.





STEP 3. Let us now try to understand how normal human color vision works using these ideas and a simulator. Open the *PhET Color and Vision* **simulator** and select the '*RGB Bulbs*' option. You will see a person facing red, green, and blue lights, each with dimmer controls attached. Slide the dimmer control on the red light up to its highest setting.

There should currently be a stream of photons[1] from the long wavelength (**R**) band of visible light entering the person's eyes. This person's (and hence our own) eye-brain system 'perceives' this as 'red light' because this wavelength band mostly 'triggers' only the '**R**' receptors in our eyes. Similarly, light from the **G** band mostly triggers our '**G**' receptors and light from the **B** band mostly triggers our '**B**' receptors.

Suppose equal intensities of light from both the **R** band and the **G** band enter our eyes together. What color do you think we would perceive and why?

Check your thinking by setting both the red and green lights in the simulator to the highest setting. What color is perceived? Is this what you predicted?

[1] In this simulation, the light is represented as tiny particles rather than as waves. Although we will not explore that model further, scientists often think of light as consisting of a stream of particles called *photons*. In the simulation, the 'particles' are colored as red, green or blue. The coloring is only a simulator representation to help you keep track of which wavelength band the particles are from; in actual fact, the particles of light are not 'colored.'

Next, check what color is perceived when equal intensities of red light and blue light enter the eye, and then when green light and blue light enter the eye.

What color is perceived when equal intensities of the **R** and **B** bands lights enter the eye together?

What color is perceived when equal intensities of the **G** and **B** bands enter the eye together?

To ensure consistency, we will use the name '***CYAN***' (**C**) for the mixture of blue and green, and the name '***MAGENTA***' (**M**) for the mixture of red and blue.

Now **predict** what you think would be perceived when equal intensities of red, green, **and** blue light enter the eye? Explain your thinking.

Before you check with the simulator, borrow a flashlight from another group and try it yourself.

What 'color' do you see when red, green, and blue light overlap? Is this confirmed by the simulator? Is it what you predicted?

Why does this result make sense in terms of which color receptors are being triggered in your eyes?

We can summarize the simple rules for mixing equal intensities of color lights as follows. We will use the shorthand notation, **R**, **G**, **B**, **W**, **Y**, **C** and **M** to represent red, green, blue, white, cyan (blue-green) and magenta (red-blue) light respectively.

R + G = Y	**R + B = M**	**G + B = C**
	R + G + B = W	

We can perceive other color lights (e.g. orange, lime green, etc.) by mixing different intensities (brightnesses) of **R**, **G** and **B** lights. Try it now with the simulator. This process is known as ***color addition***.

Finally, check what color is perceived when **<u>no light of any color</u>** enters the eye. Why does this make sense?

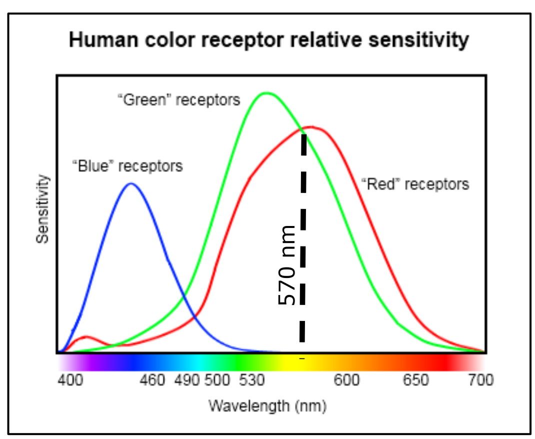
Color addition in technology

Lots of devices rely on color addition to produce a seemingly wide range of colors from just red, green, and blue. If you look very closely (with a magnifier) at a computer monitor or a TV screen, you will notice a large number of very tiny and closely spaced dots or stripes of red, green and blue (called *pixels*). When viewed from far enough away, the visual effects of these tiny pixels in a small region of the display blend together in your eye. Thus, if a certain region on the display has brightly glowing red and green pixels, but the blue pixels are turned off, then beyond a certain distance away that part of the screen will appear to a viewer to be yellow in color because it is triggering both the **R** and **G** receptors in your eye. (The Pointillist artists of the 19^{th} century, the most famous being Georges Seurat, used a similar technique with small, closely spaced dots of color paint.)

So what about yellow light?

You have seen that when a mixture of red and green light it is perceived as being yellow. However, when light of a single wavelength of around 570 nm enters our eyes, we also perceive it as yellow.

Use this graph to explain why this is.

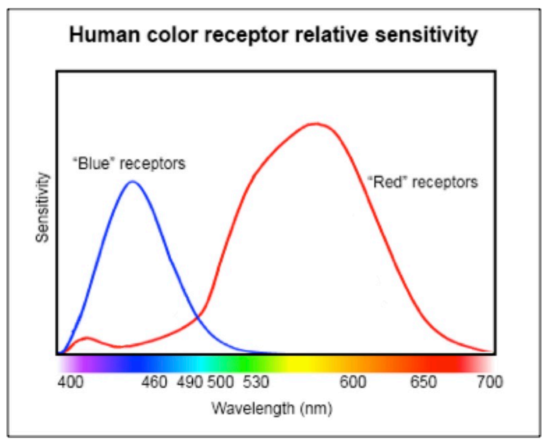


Approximately what wavelength would truly cyan light (rather than a mixture of green and blue) have? Explain your reasoning.

Exploration #2: What about eyes that have different color receptors?

In Exploration #1, we examined how normal human color vision works, by having receptors sensitive to three different color bands. This is called *trichromatic* (three color) vision. Now let us think about how we would perceive the colors around us if our eyes worked differently. We will first consider defects in normal human color vision in which one of the sets of color receptors either does not work, or is completely absent. Since such a person's eyes are only sensitive to two color bands, this is called *dichromatic* vision. Worldwide about 8% of males and 0.5% of females have such defects in their color vision.

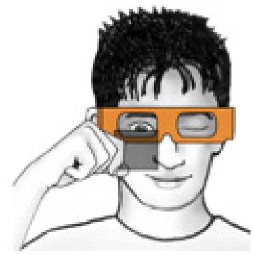
STEP 1: By far the most common defect is either low functioning or complete absence of **G** receptors (*deuteranomaly* or *deuteranopia* respectively). Therefore, the brain must determine color perception from the signals provided by only the **R** and **B** receptors.



People with normal vision can simulate this condition to some degree by looking through a color gel that blocks light from the **B**-band entering their eye, while letting the **R**-band and **B**-band through.

What color gel do you think would have these properties? Briefly explain your reasoning.

STEP 2. To check your thinking, turn on the bulb with the long straight filament and again look at it through your spectral glasses. Close one eye and focus your open eye on the color spectrum that appears to the **<u>LEFT</u>** of the bulb filament itself.



To see what each gel does, you need to compare what the spectrum looks like both **with** and **without** the gel in front of your eye. To do this, you should hold the gel in a position such that it is covering only the bottom half of the full color spectrum you are seeing. (Alternatively, you could move the gel completely in front of and then away from your open eye several times.)

As before, to make the observations and analyses simpler, we will assume that the full color spectrum is made up of only the three broad bands mentioned earlier: **red (R), green (G), and blue (B)**, and determine which of these three bands each gel removes[2] from the white light and which it 'lets through'.

NOTE: *These gels are not perfect and so in some cases, you may see a little of the other bands, but at least some parts of one or more bands should be removed, or be significantly dimmer than they are without the gel.*

For example, when you look at the spectrum through the red gel, you should see that the **R** band looks about the same both ***with*** and ***without*** the gel. This means that the **R** band is let through (***transmitted***) by the red gel. However, you should also see that, when viewed through the red gel, most of the **B** and **G** bands are missing (or at least are significantly dimmer). This means that the **B** and **G** bands are removed (***absorbed***) by the red gel.

Make observations with your spectral glasses and gels to complete the table below according to which of the **R**, **G**, and **B** bands each gel seems to remove (absorbed) and which it lets through (transmitted). The first line has been done for you. ***Remember to make allowances for the fact that the gels are not perfect!***

Table 1: Which color bands of the spectrum do each of the gels absorb or transmit?

Name of gel	Which color band(s) are *removed (absorbed)*?	Which color band(s) are *let through (transmitted)*?
Red	**G B**	**R**
Green		
Blue		
Yellow		
Cyan		
Magenta		

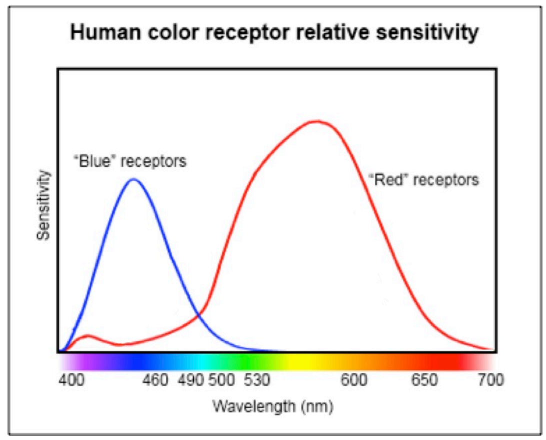
[2] When we say the a color gel 'removes' one or more color bands from the light, what actually happens is that inside the gel there is a chemical dye that has the property of absorbing a particular band or bands of light, just like the cones in our eyes.

Because these gels remove one or two color bands from the spectrum, they are often also called **color filters.** When we use gels or dyes to remove colors from light, we call it ***color subtraction***.

STEP 3. Recall that to simulate the color vision of a person whose **G**-receptors are not functioning, we want to allow the **R**- and **B**-bands to reach our eyes, but block the **G**-band.

Which color gel would be most appropriate to achieve this? Does this agree with your prediction earlier?

Put the appropriate color gel in front of one eye (closing the other one) and look at a picture of the full spectrum of colors (either printed out or displayed by your instructor). You should note the following (use the sensitivity graph to help you understand):



- There should be much less variation in the yellow/orange/red end of the spectrum. For a true deuteranope **<u>only</u>** the **R** receptors would be triggered by all these colors. When only the **R** receptors are triggered it is thought that a brownish color is perceived, so a true deuteranope would see all this end of the spectrum as the same brown color.

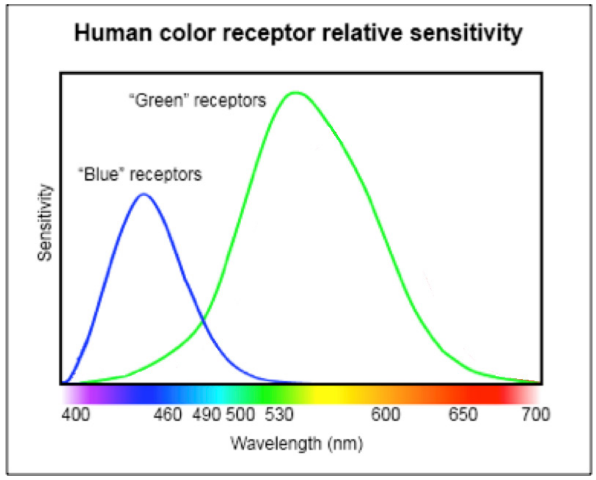
  *(**Note**: If your vision is normal you are likely seeing it as more red in color because your **G** receptors are sensitive to these colors also. so your brain is receiving a signal from both **R** and **G** of receptors.)*

- The blue/violet end of the spectrum should look somewhat similar to how to it looks without the gel. This is because the **B** receptors are mainly responsible for color perception in this range for both normal vision and deuteranopes. When only the **B** receptors are triggered it is thought that a bluish color is perceived, so a true deuteranope would still see the spectrum as blue, but with slight changes in hue determined only by the **R** receptors that still have some sensitivity in this range.

- The green region of the spectrum likely looks very dark through the gel. This is because the gel is absorbing light in this range, not not letting any of it reach your eye. ***This is NOT how a true deuteranope would see this!*** Instead light from this range would enter their eyes and would trigger both the **R** and **B** receptors, which would be perceived as a pale pinkish brown color.

So for a true deuteranope the world would reveal itself mainly in shades of blue and brown.

STEP 4: The next most common defect is either low functioning or complete absence of **R** receptors (*protanomaly* or *protanopia* respectively). In this case, the brain must determine color perception from the signals provided by only the **G** and **B** receptors.



What color gel should you look through to simulate this condition (at least somewhat)? Explain how you know.

Put the appropriate color gel in front of one eye (closing the other one) and look at a picture of the full spectrum of colors. Answer the following questions about what you should be seeing, using the sensitivity graph above to help you.

Why does the red end of the spectrum look very dark through this gel? Why would this not be the case for a true protanope?

It is thought that when only the **G** receptors are triggered, a brown color (very similar to that produced by the **R** receptors alone) is perceived.

What color would a true protanope perceive for the yellow/orange/red parts of the full spectrum, and why?

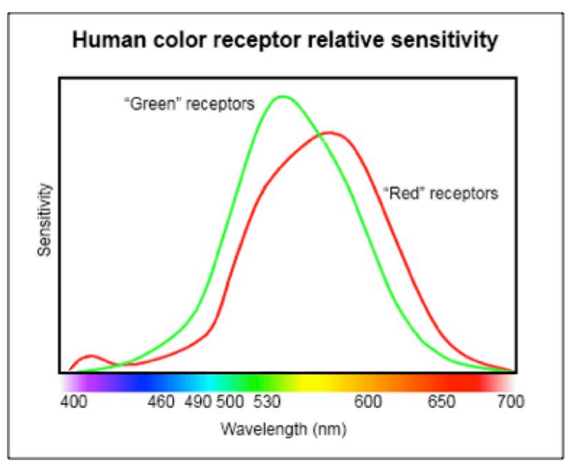
Why would a true protanope perceive the blue end of the spectrum in a similar way to someone with normal color vision?

As before the green area of the spectrum is a little trickier as it is here that all three types of receptors play a role in normal color vision. However, when light from the **G**-band enters the eye of a protanope it triggers both the **B** and **G** receptors and this is thought to be perceived as a pale yellowish brown.

Thus, for a true protanope the world would again seem to consist of shades of blue and yellow/brown. In fact, it is thought that protanopes and deuteropes see colors in very similar ways. This is not too surprising since the **R** and **G** receptors have similar sensitivity ranges. They both have trouble telling the difference between what normal vision sees as red and lighter greens, as both appear to them as shades of yellow/brown. For this reason, people with either of these forms of dichromatic vision are often said to be red-green colorblind, and tests for this rely on not being able to distinguish patterns in a mix of these colors.

Check your understanding

By far the rarest form of dichromatic vision is that in which the **B** receptors are either low functioning or complete absent. (*tritanomaly* or *tritanopia* respectively). In this case, the brain must determine color perception from the signals provided by only the **R** and **G** receptors.



What color gel should you look through to simulate this condition (at least somewhat)? Explain how you know.

Put the appropriate color gel in front of one eye (closing the other one) and look at a picture of the full spectrum of colors. Answer the following questions about what you should be seeing, using the sensitivity graph on the previous page to help you.

Why does the red end of the spectrum look very similar both with and without the gel in front of your eye? What does this tell you about how a true tritanope sees this end of the spectrum?

Why would the green part of the spectrum look slightly different to a true tritanope?

The blue end of the spectrum would appear quite dark to a true tritanope. Why is this?

One test for tritanopia is to show a person patterns that are made of a mixture of black and dark blue dots. How does this work?