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Color Is in the Eye, and Brain, of the Beholder

The way we see and describe hues varies widely for many reasons: from our individual eye structure, to how our brain processes images, to what language we speak, or even if we live near a body of water

By Nicola Jones, Knowable Magazine on November 1, 2022

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What color is a tree, or the sky, or a sunset? At first glance, the answers seem obvious. But it turns out there is plenty of variation in how people see the world—both between individuals and between different cultural groups.

A lot of factors feed into how people perceive and talk about color, from the biology of our eyes to how our brains process that information, to the words our languages use to talk about color categories. There's plenty of room for differences, all along the way.

For example, most people have three types of cones—light receptors in the eye that are optimized to detect different wavelengths or colors of light. But sometimes, a genetic variation can cause one type of cone to be different, or absent altogether, leading to altered color vision. Some people are color-blind. Others may have color superpowers.

Our sex can also play a role in how we perceive color, as well as our age and even the color of our irises. Our perception can change depending on where we live, when we were born and what season it is.

To learn more about individual differences in color vision, *Knowable Magazine* spoke with visual neuroscientist Jenny Bosten of the University of Sussex in England, who wrote about the topic in the *2022 Annual Review of Vision Science*. This conversation has been edited for length and clarity.

How many colors are there in the rainbow?

Physically, the rainbow is a continuous spectrum. The wavelengths of light vary smoothly between two ends within the visible range. There are no lines, no sharp discontinuities. The human eye can discriminate far more than seven colors within that range. But in our culture, we would say that we see seven color categories in the rainbow: red, orange, yellow, green, blue, indigo and violet. That's historical and cultural.

Is that what you taught your own kids, now aged 10 and 5?

I didn't teach them anything about color because I was interested in observing what they naturally thought about it. Like, for instance, my daughter, probably at the age of 5, said: "Are we going to the blue-sky building?" To me, it looked white. But it was illuminated by a blue-sky light. There's also an anecdote that I've heard—I don't know if there's any solid evidence for this—that children can sometimes initially call the sky white, and then later they learn to perceive it as blue. I was interested in observing all these potential things in my own children.

Surely most people around the world agree in general about the main, basic colors, like red, yellow and blue. Don't they?

There are several big datasets out there looking at color categorization across cultures. And the consensus is that there are some commonalities. This implies that there might be some biological constraints on the way people learn to categorize color. But not every culture has the same number of categories. So, there's also this suggestion that color categories are cultural, and cultures experience a kind of evolution in color terms. A language might initially make only two or three distinctions between colors, and then those categories build up in complexity over time.

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In some languages, like old Welsh for example, there's no distinction made between blue and green—they both fall into a kind of "grue" category. In other languages, a distinction is made between two basic color terms for blue: In Russian, it's *siniy* for dark blue and *goluboy* for lighter blue. Do speakers that make that distinction actually perceive colors differently? Or is it just a linguistic thing? I think the jury's still out on that.

There was an explosive debate online in 2015 about "The Dress," and whether it was white and gold or blue and black. Why did people see it so differently?

Scientists got very interested in that particular image, too. And there's been a lot of research on it: there's even a [special issue of a journal](#) devoted to the dress. A consensus has emerged that the way you see the dress largely depends on what lighting you assume it to have. So, people who see it as blue and black see the dress as brightly illuminated by a yellowish light. And people who see it as white and gold see it as more dimly illuminated by a bluish, more shadowy light. Ultimately, it's the brain that's making the judgment, about what kind of illumination is on the dress.

But then the question is, why do some people think that is illuminated by bright yellow, and others by a dimmer blue? It could be your own experience with different lighting conditions, and which ones you're more familiar with—whether you're used to blue LED light or warm sunlight, for example. But it could also be influenced by other factors like, for example, [changes that happen to your eyes as you age](#).

One of the most obvious reasons why people might see color differently is because their cones might be different: There might be genetic variations that affect the biology of the light detectors in their eye. How many kinds of variations are there like this?

There are many, many combinations. There's three cone types. We know more about the variation in two of those: the ones that detect long and medium wavelengths, known as L and M cone types. Each of those has a photosensitive opsin, which is the molecule that changes shape when light is received, and which determines the cell's sensitivity to wavelength. The genes that code for each opsin has seven sites in the gene that are polymorphic: They can have different letters of DNA. You can have different combinations of those seven variants. The total number is large.

One common variation is red-green color blindness. What causes that?

That would be an abnormality in either the L or the M cone types. In dichromacy—that's the severe form of red-green color vision deficiency—you'd be missing either the L or the M cones, or they'd be there but non-functional.

Red-green color vision deficiency is also called Daltonism, after John Dalton, the English chemist from the 1790s. It wasn't super obvious to him that his color vision differed from the majority. But he noticed a few cases where his descriptions of color differed from those of other people around him but were shared with his brother. He thought it was to do with an extra filter within the eye. But then, many years later, [others were able to sequence his DNA](#) and they could show that he was a dichromat.

In the mild form, anomalous trichromacy, you'd still have two different cone types, but they would just be much more similar to each other, in terms of the wavelengths of light that they are optimized to detect, than they are normally. So, the range of perceived differences between red and green would just be reduced.

What does the world look like to those who have the more severe case?

For a dichromat, they're essentially missing a whole axis of color vision, and their color vision is then one-dimensional. In terms of how it looks, it's quite hard to say because we don't know what, subjectively, the two poles of that dimension are. What's preserved is the axis between violets and lime green in a normal color space. So that's often how it's portrayed. But really, it could be any two hues that are perceived. We just don't really know.

There have been some cases where people have been dichromatic in one eye only. And then you can ask them to match the color they see from the dichromatic eye to colors presented to the normal, trichromatic eye. And in those cases, sometimes they see more from the dichromatic eye than we expect. But we don't know whether that's typical of a regular dichromat who doesn't have the trichromatic eye to help wire up their brain.

Do these variations from the norm always make the world less rich in terms of color? Or can some genetic variations actually enhance color perception?

Anomalous trichromacy is an interesting case. For the most part, color discrimination is reduced. But in particular cases, because their cones are sensitive at different wavelengths, they can actually discriminate certain colors that normal trichromats can't. It's a phenomenon called observer metamerism.

Then there's tetrachromacy, where a person with two X chromosomes carries instructions for both an altered cone and a regular one, giving them four kinds of cones. We know that this definitely happens. But what we don't know for sure is whether they can use that extra cone type to gain an extra dimension of color vision, and to see colors that normal trichromats can't see or can't discriminate.

The strongest evidence [comes from a test](#) where observers had to make a mixture of red and green light match a yellow; some individuals couldn't find any mixture that would match the yellow. They would actually need three colors to mix together to make a match, instead of two. It's as if there are four primary colors for them, instead of the usual three. But it's hard to prove how and why that's happening, or what exactly they see.

Do these people know they have color super-vision?

The women that we recruited didn't know their color vision status. More than 50 percent of women have four cone types. But, usually, two of them are just very subtly different, so that may not be enough to generate tetrachromatic vision.

Your own subjective experience of color is so private, it's hard to know how your color vision compares to the people around you. John Dalton was the first person to identify red-green color blindness, in 1798—that's really quite recent. He had a severe type. But even that wasn't totally clear cut for him.

Are there other biological differences, beyond genes, that affect color vision?

Yes. The lens yellows with age, especially after the age of 40, and that reduces the amount of blue light that reaches the retina. There's also the macular pigment, which also absorbs short, blue wavelengths of light. Different people have different thicknesses of that depending on what they eat. The more lutein and zeaxanthin you eat, substances that come from vegetables like leafy greens, the thicker the pigment. Iris color also has a small correlation with color discrimination: It could be a factor in determining your very precise experience of color. Blue eyed people seem to do slightly better in tests of color discrimination than brown eyed people.

Is our color perception also affected by the world around us? In other words, if I grow up in a green jungle, or a yellow desert, would I start to discriminate between more colors in those regions of the rainbow?

Yes, it can be. And that that's quite a hot topic of research at the moment in color science. For example, whether there's a separate word for green and blue seems to depend, in part, on a [culture's proximity to large bodies of water](#), for example. Again, that's a linguistic thing—we don't know whether that affects their actual perception.

There's also a seasonal effect on perception of yellow. There was a study in York, which is quite gray and gloomy in the winter and nice and green in the summer, and they found that the wavelength that people [perceived as pure yellow shifted with the season](#)—only by a small amount, but still a measurable amount.

And there's also been an effect observed from the [season of your birth](#), especially if you were born in the Arctic Circle. That is probably to do with the color of light that you're exposed to during your visual development.

The effect of the environment can affect perception in two opposite ways though: Different environments can contribute to individual differences in perception, but a shared environment can also counteract biological differences to make people's perceptions more similar.

Wow. There are so many differences, and it seems so hard to unpick it all, and know whether those differences are biological or cultural. It really makes you go back to that philosophical conundrum: When I see blue, is it the same blue that you see?

Yes. I've always seen color as something really fascinating, especially the subjective experience of color. It's still a complete mystery, how the brain produces that. I've always wondered about it, long before I decided to commit to the topic academically.

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ABOUT THE AUTHOR(S)

Nicola Jones is a freelance science reporter and editor who lives in Pemberton, British Columbia. Read more about her and her work on her [blog](#).

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