Kristen

So I guess it all started really before I was ever born. When my parents were dating, it sort of naturally came up that my dad has color vision deficiency and my mom at the time acknowledged that she had experience with that because her dad has color vision deficiency as well. And at the time they really didn't think too much of it, it was something cool they had in common and really didn't devote a lot of consideration to it. But eventually they got married and they had my brother and then they had me. So when my brother was, I wanna say a toddler, he started displaying some patterns that would be consistent with color vision deficiency. And funny enough, my mom is an optometrist, so she's really well versed in how this works. So she knew that this was a consideration.

And so they went and they had my brother tested and it turns out he had color vision deficiency. Now he's a couple years older than I am and so I have two X chromosomes, it's not totally normal for people like me to have this. And so my parents were really not concerned until I started displaying those same patterns. And that's when it all finally clicked that my dad having color vision deficiency, my grandpa having color vision deficiency pretty much created this scenario that normally doesn't occur until your 9th grade biology class, where I had the possibility to be a female with color vision deficiency. So growing up it was a household of my dad, my mom, my brother, and myself. So actually color vision deficiency was the quote unquote "normal" way to be. So we all have deuteranomalies. So that's the red-green color vision deficiency and so it's the most common I think of all of them. The three of us all have it.

My mom doesn't but she's an optometrist, so this is always the ideal scenario. So there's going to be one person in your house that doesn't see the way you all do, it's kind of nice that she's at least an expert in this situation. I would say growing up it was never really a concern, it maybe came up on occasion. But my parents were very proactive about letting my teachers know that this was just something we all had. But one of the best parts of being a female with color vision deficiency is that it's on both sides of my family. So on my mom's side, I have a bunch of cousins and they have it too. And so we all like to say we're better than the other cousins or whatever it is you do in families. And then on my dad's side, he's somewhat unique but his maternal grandfather, so my great grandpa lived a very long life and we all had the opportunity to get to know him. So it was this big thing that we're all kind of proud to have.

So one of the stories that we were always told about my great grandpa is that in WWII when they were trying to get people to enlist, he volunteered early hoping they would look the other way and allow him to fly planes. They definitely did not allow him to fly planes. But something they always tell us is a supposed advantage to having color vision deficiency is that camouflage doesn't work as well. And so one of the things they had him doing was trying to spot really any sort of activity that other members of his squadron really couldn't see. And so he was the designated 'see the camouflage' guy. So this was always just sort of an interesting story that was told to us but I do want to take it with a grain of salt because I never actually heard it from my great grandpa himself. He did not like to talk about his experiences during the war. But it was always kind of a funny side note.

Growing up with color vision deficiency in my family, again, it was so normal but then getting out into the supposed real world now that I've moved out, gone to college and everything, there have been a couple of things that are very challenging. So I'm working on my PhD and we do nutritional immunology and microbiology. And so a lot of that encompasses the microbiome research and heat maps are a big part of it. And most heat maps usually go from red to green. But being red-green colorblind, that's really challenging. And you can't be the person at the conference who stands up and can't read their own data. So my really awesome collaborators actually came up with a new color scheme that would work for me. And according to everyone else, it's really, really ugly. So I think it goes from blue to black to yellow. And I can see it really well but I've definitely been at conferences or given talks in my department where people have actually said that's all great but your colors are ugly, or these are really, really bad.

	And that puts you in this really awkward situation where you have to stand up in front of all these people and say yes, I understand they might look bad, but those colors are for me, they're not for you. And so it does end up becoming sort of an awkward teachable moment where they have to acknowledge that there are people in the room and there's a good likelihood that there are people in the room who just don't see colors the same way as you. But then also having to stand up and say yes, I am a female, I'm colorblind, and then that starts a whole different conversation that isn't about the science I just presented, it's about me.
	And then the other biggest challenge I would say is that because it's not likely for females to be colorblind or to have this sort of color vision deficiency is that some people were taught most simplistically that it's impossible. So it's not that they were told it's unlikely, they were just told by some teacher along the way that it was totally impossible. And so when you tell them this about yourself, they look at you funny, they come at you with sort of a negative approach like you must be lying to get attention, you're making this up. So that always is really a challenge because it's trying to overcome that impression that didn't really need to be an impression in the first place. And so all of that has been somewhat of a challenge but ultimately I think the best thing that comes out of it is just being part of this community.
	I think it's really funny when you catch people off guard with it because you can't look at someone and see this. So it's nice to get a few jokes in there. A lot of times I'll tell my friends that my favorite M&Ms are the gray kind, even though I can see those colors, it's still just always catches people off guard. I think my biggest thing that I get asked is if I would ever consider using those color vision correction lenses. And my biggest answer is a resounding no. I was born this way, I've always seen the world this way, I don't want anything different. The glasses aren't guaranteed to work. And so I don't want to run the risk of seeing things differently and ending up unhappy. So I would say that's kind of the main part of my story is that I just love being this way. It's a challenge most times but it's a lot of fun when you can make it fun. And just proves that my brothers were always wrong when they said I was adopted. So yeah, I think that's pretty much the main part of my story.
TPWKY	(This Podcast Will Kill You intro theme)
Erin Welsh	Thank you so much, Kristen, for sharing your story with us.
Erin Allmann Updyke	We really appreciate it.
Erin Welsh	Hi, I'm Erin Welsh.
Erin Allmann Updyke	And I'm Erin Allmann Updyke.
Erin Welsh	And this is This Podcast Will Kill You.
Erin Allmann Updyke	Welcome. Today we're talking about the whole spectrum, get it, of color vision deficiencies.
Erin Welsh	It actually took me a second to get it. I think I'm too close to this thing, Erin.
Erin Allmann Updyke	That's the only joke I have for the whole episode.
Erin Welsh	Yeah, I don't think I have any jokes which is really surprising. Again, I was like too much in the weeds, I lost the forest for the trees.
Erin Allmann Updyke	Yeah.

Erin Welsh	Whoops.
Erin Allmann Updyke	We're really selling it.
Erin Welsh	Yeah. But no, I mean that's the thing though, that there is just so much to go into with this and it's all really interesting. Like honestly, it's like you could throw a dart at a dartboard and find 1000 interesting things about one aspect of the history of biology of color vision deficiencies.
Erin Allmann Updyke	Yeah. You might have to open like no less than 50 Wikipedia pages to understand one paper, for example.
Erin Welsh	I know. I could not tell what was like on my Chrome. I was like oh my gosh, this is way too many tabs. I need to deal with this. My life. Well it's going to be a great episode but before we get into the meat of it-
Erin Allmann Updyke	It's quarantini time.
Erin Welsh	It is. What are we drinking this week?
Erin Allmann Updyke	We're drinking True Colors.
Erin Welsh	And I love this title because is there any such thing as true color?
Erin Allmann Updyke	That's how the song goes, right?
Erin Welsh	I see your true colors shining through.
Erin Allmann Updyke	There you go.
Erin Welsh	Yeah. (singing) That's why I love you. I'm going to keep that in.
Erin Allmann Updyke	Erin, what is in True Colors?
Erin Welsh	In true colors, it is a fun little summery concoction. It has basically as many colors as we could try to fit in there, which is not that many because I'm not a skilled layerer when it comes to quarantini-making. But there's grenadine and then there's orange juice and then there's blue curaçao, and there's lime juice and rum.
Erin Allmann Updyke	Yum.
Erin Welsh	It's great.
Erin Allmann Updyke	We'll post the full recipe for that quarantini as well as our non-alcoholic placeborita on our website thispodcastwillkillyou.com.
Erin Welsh	We certainly will. On our website thispodcastwillkillyou.com, I'm going to pull it up and just see what I can find.
Erin Allmann Updyke	Love that.

Erin Welsh	Because my brain has not been functioning very well today. We've got transcripts, we've got the sources for each and every one of our episodes, we've got a firsthand account form. I don't think I've been saying that in the past most recent episodes.
Erin Allmann Updyke	Oh yeah, we've missed it.
Erin Welsh	We have got links to bookshop.org affiliate account, Goodreads list, our merchandise page, music by Bloodmobile, Patreon. Lots of stuff. Check it out, it's good stuff.
Erin Allmann Updyke	With that, shall we talk about color vision deficiencies?
Erin Welsh	I think we should.
Erin Allmann Updyke	Okay. Right after this break.
TPWKY	(transition theme)
Erin Allmann Updyke	To be able to talk about color vision deficiencies, aka colorblindness, I think we first have to understand at least a little bit about color vision itself, right?
Erin Welsh	It's easy, right?
Erin Allmann Updyke	So simple and straightforward to explain on a podcast in under two hours. Here we go. At the most basic level, just like bare bonesing it, we as humans are able to distinguish between colors in the visible spectrum because our brain can compare information that it receives from three different sets of cells that contain photoreceptor proteins in our eyes. I'm gonna go into a bit more detail about how that process works. And I think once we understand the really bare basics of that process, I think the many, many ways in which this system can have deficiencies, aka all the variations of color vision deficiency, become pretty obvious or at least relatively so. Okay?
	So going all the way back to the beginning of time kind of, light exists as a spectrum. I actually have no idea if that has anything to do with the beginning of time. But anyways, light exists as a spectrum. There is an infinite number of wavelengths of light that exist from ultraviolet to infrared, 400 to 800 nanometers. Our human eyes have evolved to see a fairly small portion of this spectrum of light, visible light, ROYGBIV, in our rainbows. So it goes like this. Light, all of its various wavelengths, comes into our eyeballs, travels through our eye goo, and hits onto our retina at the very, very back of our eyes. And in this retina, which is just the area in our eye, there exists a whole bunch of different cells that are full of photoreceptor proteins. There are two main types of these photoreceptor cells, rods and cones. Rod cells express a protein called redoxin, it mostly helps us have vision in dim light. So we get to ignore it for this episode. Okay?
Erin Welsh	Yay.
Erin Allmann Updyke	Yay, finally something. It's probably marginally involved, etc, but for the purposes of today, rods, dim light. It's the cone cells that allow us as humans color vision. So these cone cells, which are super densely packed within our retina, come in three different flavors or rather they express three different kinds of opsins, which are these photoreceptor proteins. Each one of these opsins is most sensitive, peak sensitive to a specific wavelength of light: short, medium, and long.

Erin Welsh	Simple enough.
Erin Allmann Updyke	Simple enough so far. So the short wavelength sensitive opsin is also called the blue cone. The middle or medium wave sensitive opsin is also called the green cone. And the long wave sensitive opsin is called the red cone, even though its peak wavelength of absorption is actually yellow, not red, but let's ignore that and call it red.
Erin Welsh	Great.
Erin Allmann Updyke	Yeah. So the waves of light hit these photoreceptor cells, they are absorbed by these proteins, very complex chemistry happens, and then those wavelengths, that energy is translated into electrical signals that travel via our optic nerve to a part in the middle of our brain, in our thalamus, and then to the primary visual cortex which is in the back, the occipital lobe of our brain. And that's where all of this visual information, everything that we see including color information, is processed and interpreted. That is the most basic way that we can explain how color vision happens.
	The short wavelengths or blue sensitive cones respond to a much more discrete array of wavelengths of light. Like if you look at all of the spectra that they can absorb, it's more offset. Whereas the middle green and the long red wavelength cones have much more overlap, if you look at all the wavelengths that they're sensitive to. But they all three have different peaks. And this is really important because none of these cone cells alone allow us to see or distinguish colors on their own. Our brain has to compare the information that it gets, the signals from each of these different types of cells. And in doing that, it's then able to differentiate colors into our human trichromatic or three color vision system.
Erin Welsh	Right. You need at least two for comparison. But three, you just get to compare more and split up that spectrum more.
Erin Allmann Updyke	Exactly. And speaking of only two, a lot of mammals in fact have only two sets of cones. That's why people say like dogs are colorblind. They're not colorblind but they only have two sets of cones. Humans and some primates have three. What's very cool is that fish have like four and some birds have five.
Erin Welsh	Oh yeah. It's like wild.
Erin Allmann Updyke	I know.
Erin Welsh	And people thought that fish were colorblind forever.
Erin Allmann Updyke	Oh I know. I love it. I mean they can see UV, for goodness sake.
Erin Welsh	Right. So many things can see UV.
Erin Allmann Updyke	I know. But not us.
Erin Welsh	I know.
Erin Allmann Updyke	Do you know I learned it's mostly because of our lens, not because our cones are not sensitive in that wavelength?

Erin Welsh	Oh yeah. Interesting.
Erin Allmann Updyke	Our lenses filter out the UV and that's a large part of why we can't see UV.
Erin Welsh	Because as like protect from damage?
Erin Allmann Updyke	Oh don't ask me about the whys, Erin. It has nothing to do with this episode so I didn't dig into it.
Erin Welsh	Those are my favorite questions to ask.
Erin Allmann Updyke	I know, I know, I know. Okay. But getting back to it, obviously these cone cells therefore are very important. And in addition to allowing us to perceive color vision, cone cells also have a faster response time to various light stimuli and they help us a lot in fine detail perception because they can perceive rapid changes in images. So our cone cells are very, very important to our overall human vision system. So color blindness or color vision deficiency is what happens when there are problems with this visual processing. Because like we said, you need all three of these cones to be functioning and specifically to be responding to the specific wavelengths of light that we expect to be able to distinguish the color spectrum that we associate with human color vision.
	So there's a lot of different ways that this can go a little, shall we say, wonky. The vast majority of color vision deficiencies are congenital, meaning they are inherited. They are from mutations in our genetic code. These mutations can happen in genes that encode for the cone cells or for the opsins themselves, or they can happen because of mutations in the promoter regions for any of those genes, like the regions that tell our cells to turn on or off, the expression of those genes. And that process gets incredibly complicated. So this is not by any means a one gene, one disease type scenario that we have here. There are many, many, many possible mutations that result in a wide variety of color vision deficiencies, which we'll get into all of the details of.
	There also, in addition to hereditary color vision deficiency, is acquired color vision deficiency. And that can happen from damage to parts of our eye during our lifetime. This can happen from other congenital diseases that aren't directly related to say our cone cell function but it also can happen just from direct damage from various eye illnesses. For the purposes of this episode, because that's a lot, I'm mostly focusing on the congenital rather than the acquired color vision deficiencies. But I have a couple of papers if people want to read more about the other side. So let's get into like what does color vision deficiency even mean.
Erin Welsh	Yeah.
Erin Allmann Updyke	Okay. So the mildest forms of CVD, can you just call it that?
Erin Welsh	Sure.
Erin Allmann Updyke	Are called anomalous trichromacy. So humans are trichromatic, so we have three sets of cones, three peak wavelengths of color vision. A lot of people with color vision deficiency still have these three separate sets of cones, three separate sets of opsins, but they have some kind of mutation that results in a shifting of the frame, if you will, the shifting of that peak wavelength of sensitivity, so that there's more overlap between the peaks, so that the information that your brain gets about those different wavelengths can't be separated out as easily.

Erin Welsh	And so when you say that there's a shift, is it they're moving closer together and it's all three of them? Or is it just one that happens to move closer to the other one?
Erin Allmann Updyke	Such a good question. There's three different possibilities.
Erin Welsh	Okay.
Erin Allmann Updyke	So in deuteranomaly, deuter you'll hear me say a lot, I think it has something to do with green. Anyways in deuteranomaly, the middle wavelength photopigment is mutated so that it's more similar to the long wavelength photopigment. So when you should be able to absorb the peak in the green zone, now that specific cone looks a lot closer to the red zone.
Erin Welsh	Okay.
Erin Allmann Updyke	Now the opposite can happen as well. In protanomaly, the long wavelength photopigment, the red, is mutated so that its peak is really similar to the middle wavelength. So what should be absorbed in the red zone is shifted to the green. Does that kind of make sense?
Erin Welsh	Kind of. So in terms of like the result, like what resolution you lose in terms of color distinguishing or the colors that are typically called whatever colors we have in our visual spectrum, you know what I mean?
Erin Allmann Updyke	Totally. Yeah, so you're right. You lose some of that distinction. So you're not able to distinguish between say certain hues or between certain colors.
Erin Welsh	Okay. And so for deuteranomaly, you lose the ability to distinguish between reds and greens. And for protanomaly, it's also reds and greens.
Erin Allmann Updyke	Yeah.
Erin Welsh	But like it's slightly, the shading is different?
Erin Allmann Updyke	That's exactly right.
Erin Welsh	Okay.
Erin Allmann Updyke	100% right.
Erin Welsh	Okay, cool.
Erin Allmann Updyke	And those overall are the two most common forms of color vision deficiency.
Erin Welsh	And so that is not caused by a lack of opsin.
Erin Allmann Updyke	Yeah.
Erin Welsh	But just a shift in the opsin.
Erin Allmann Updyke	Exactly. They often result from unequal recombination. So what you get are these hybrid gene formations, the details of it.

Erin Welsh	That's fascinating.
Erin Allmann Updyke	I know.
Erin Welsh	I thought it was just an absence of a cone.
Erin Allmann Updyke	Oh we're getting there.
Erin Welsh	Okay.
Erin Allmann Updyke	We're getting there.
Erin Welsh	Okay.
Erin Allmann Updyke	We are nowhere near done. So there's also tritanomaly which would change the peak of the blue cone, right. Tritan because we talked about the red cone and the green cone, tritan means blue. This would change the peak of the blue cones. Overall this is far less common. And if you remember that I mentioned that the L and the M have a lot more overlap to begin with.
Erin Welsh	Right.
Erin Allmann Updyke	Tritanomaly alone may not result in that big of a deficiency depending on how much it's shifted, if that makes sense.
Erin Welsh	Right, right. Yeah.
Erin Allmann Updyke	Now overall those three types, again, are called anomalous trichromacy. You still have all three cones. They usually result in milder color vision loss but there's a lot of variation in the ability to distinguish between shades and colors. Now then we move on to dichromacy. You can imagine this means two sets of cones. This is obviously more severe and means that you're having loss of function of one of the cone types entirely, either red, which is called protanopia, green, which is called deuteranopia, or blue, tritanopia. Here's where it gets even more interesting though is that this can happen by say the loss of one of these genes entirely. And for a long time, it was thought that that is how it happens. But it can also happen by replacement of one of these genes with the equivalent, say for example during recombination you end up with two sets of M genes instead of an M and an L.
Erin Welsh	Right. So you have like two green cones, one red cone.
Erin Allmann Updyke	Beautiful. Exactly. And then one blue. Pretty cool, right?
Erin Welsh	Yeah.

Erin Allmann Updyke	So that is dichromacy. Then there is the most severe form of color vision loss and that is monochromacy, aka the complete absence of color discrimination. Because like we said, you have to be able to compare to be able to distinguish between colors. This is by far the most rare and there still are several different forms of this. Part of the reason that true monochromacy is so rare is because while the M and the L cones, or rather the genes that encode the M and the L opsin, green and red, they sit right next to each other on the X chromosome. But the S cone or the blue cone opsin gene is all the way over on chromosome 7. It's nowhere near M and L. So to have true loss of all three of these would be incredibly rare. There is however a form of monochromacy known as blue cone monochromacy or X-linked recessive incomplete achromatopsia, where you have no functioning M or L cones and you only have functioning blue cones.
Erin Welsh	Okay.
Erin Allmann Updyke	But remember that I mentioned that cones are responsible for a lot more than just color vision, they aid in our visual acuity and things as well. So when we get to the point of monochromacies and incomplete or even complete achromatopsia, where we have like say no functioning cones, you're not just losing the ability to distinguish colors, you're also losing a lot of visual acuity. So people with monochromacy or complete achromatopsia would have significant overall visual field deficits as well. But if we kind of sum all of those fancy words up, if you hear the term red-green color blindness, that refers to any of those different possible mechanisms of the loss of distinction between red and green. So red-green color blindness includes deuteranomaly, protanomaly, deuteranopia, and protanopia.
Erin Welsh	Okay, that makes sense.
Erin Allmann Updyke	Right. Because whether we're talking about a functional loss or just a shift in spectral sensitivity, the end result is that distinguishing the wavelengths of light that make it into our eyes between red and green becomes really difficult because our brain essentially just doesn't receive enough information to make those comparisons and computations. And all four of those disorders are X-linked recessive traits. So the presence in general of one X chromosome with a functioning M and a functioning L gene is enough to result in quote unquote "normal" color vision discrimination. With the exception that because of X inactivation, which we talked about all the way back in our Turner Syndrome episode, but basically what happens when people have two X chromosomes instead of just one is that one of those Xs gets turned off. And because that can happen relatively randomly sometimes, it's also very possible to have color vision deficiency even if you carry a normal or an M and an L X chromosome. But in general, that is why we see red-green color blindness be far more common in males who are XY than in females who are XX.
Erin Welsh	Yeah.
Erin Allmann Updyke	Now blue-yellow deficiencies, called tritan deficiencies, are overall exceedingly rare compared to red-green color blindness. But these are autosomal dominant when they are present because they're on chromosome number 7. And they generally happen from missense mutations like complete pretty severe mutations that happen in the blue cone opsin sequence.
Erin Welsh	Okay.
Erin Allmann Updyke	Whereas the M and the L, which sit again right next to each other on the X chromosome, they kind of just get mixed up all the time. And that's why there's such variation in the possible anomalous expression of these two genes.

Erin Welsh	Okay, interesting. Question.
Erin Allmann Updyke	Okay.
Erin Welsh	I came across in my reading for this and I didn't really look into it too deeply. Tetrachromacy in humans. Is it real? Does it exist?
Erin Allmann Updyke	So glad that you asked. So glad. So let me tell you. I can't believe I can answer your question, Erin. So tetrachromacy would mean four color vision channels essentially instead of three. So if we remember what I just said, that the most common forms of color blindness are forms of anomalous trichromacy where you still have three sets of cones, blue, green, red. But the peak sensitivity of one of these cones, generally a red or green, is shifted. So here's where things can get fun. In a person with two X chromosomes who is heterozygous for this allele, what they can end up with is one X chromosome that has a typical M and an L and another one with a normal M and say an L prime, a slightly shifted version of L that's closer to M for example. Now in the retina of this person's eye, in every cell only one copy of the X chromosome is actually expressed at any given time. But it's very possible that in some cells, the quote "normal" X chromosome is expressed and in others the quote "mutant" X is expressed. Because it's not always the same X that gets inactivated in every cell. So that means that this person has four types of cone cells being expressed, S or blue, M or green, and then L and L prime.
Erin Welsh	Right.
Erin Allmann Updyke	So this can provide essentially a fourth color channel or tetrachromacy that at least in theory, if our brain was plastic enough, could use to interpret and distinguish between additional colors and shades.
Erin Welsh	What do you mean by if our brain was plastic enough?
Erin Allmann Updyke	Well our brain has evolved to be trichromatic. So what we don't know is does our optic nerve have enough to be able to distinguish those four color channels? Can our brain like change enough to be able to interpret those as separate or does it just collapse the L and the L prime together?
Erin Welsh	Right, okay. But this could happen with any one of those opsins?
Erin Allmann Updyke	Yes in theory, in practice it's going to be red or green most likely.
Erin Welsh	Okay.
Erin Allmann Updyke	Yeah.
Erin Welsh	Okay, interesting. Yeah because there are, like we talked about, lots of animals that have more than three cones but it's unclear with tests whether they're able to distinguish among the colors that they should be able to based on our interpretation of the science behind it.
Erin Allmann Updyke	So I love that you said that because I do feel like one thing that's so important when we talk about these color vision deficiencies is that whenever we're talking about color vision, it's like in comparison to who or to what, right?
Erin Welsh	Right.

Erin Allmann Updyke	There's another paper that I will link to that looks at specifically people with deuteranomaly, so that is red-green color blindness from a shifted green cone that they call L prime because it's now closer to a typical L or red cone, right, the green shifts to red. And what this shows is that some people with this type of color vision quote unquote "deficiency" were actually able to separate out tones, distinguish between tones that looked the same to quote "normal" color vision or trichromatic color vision observers. So there's a theoretical basis both with certain types of deuteranomalies and with this theoretical trichromacy that people could be distinguishing between shades and between colors differently. It's very, very difficult to test for. And I'll be honest, I don't understand the tests that they describe in these papers. Because to the vast majority of the population who's trichromatic, how can you determine if someone else can distinguish something that you cannot distinguish?
Erin Welsh	Right.
Erin Allmann Updyke	Right?
Erin Welsh	Yeah.
Erin Allmann Updyke	It's very difficult. I will say there is like one person I think that I read about who happens to live in San Diego, who in tests seems to have an actual functional tetrachromacy.
Erin Welsh	Okay.
Erin Allmann Updyke	Meaning that she tests where she can distinguish between additional shades and colors based on wavelengths then a trichromat can. One so far out of all of the people that I read about that were tested.
Erin Welsh	Okay, okay.
Erin Allmann Updyke	But it's really, really interesting.
Erin Welsh	That's fascinating. And I feel like there's so much there in terms of like the evolutionary history of color vision period where it's like the information that color gives you.
Erin Allmann Updyke	Yeah.
Erin Welsh	Yeah. Anyway, interesting.
Erin Allmann Updyke	Well to that point, Erin, where did this color vision deficiency thing come from, huh?
Erin Welsh	Oh gosh. Yeah.
Erin Allmann Updyke	You're going to say the word evolution.
Erin Welsh	Yeah. We're gonna have to go way further back than just that. And I guess we should get started right after this break.
TPWKY	(transition theme)

Erin Welsh	So Erin, you just took us through how we see color and what happens when people see color differently or not as many colors or no colors at all. And later in the history section, I want to explore when we first learned about these variations in color vision and color vision deficiencies. But before we get into that more like medical history side of the story, I want to try to answer the question why do we see color?
Erin Allmann Updyke	Ooh.
Erin Welsh	Humans, other primates, birds, dogs, fish, other animals. Why did color vision evolve? What purpose does seeing in color serve? Multiple purposes? You betcha. And of course not everything in biology has to serve an evolutionary purpose. But the fact that there's variation in color vision and patterns in that variation, the fact that it has evolved multiple times independently and in different ways, these things all suggest that color vision does serve a purpose. But color vision, even dichromacy is not universal among animal species. Sloths, armadillos, whales, raccoons, cephalopods, many animals are monochromats and they do just fine.
Erin Allmann Updyke	Stop it, raccoons?
Erin Welsh	Raccoons apparently.
Erin Allmann Updyke	I mean I guess they're nocturnal.
Erin Welsh	Yeah.
Erin Allmann Updyke	So that kind of tracks but I did not know that about those little buggers.
Erin Welsh	Yeah.
Erin Allmann Updyke	And sloths!
Erin Welsh	I know, I know.
Erin Allmann Updyke	Okay. I'm learning a lot.
Erin Welsh	Color vision is not necessary for survival as an individual or as a species. And in fact, some research suggests that red-green color vision deficiency has been selected for in some animals. So what does color vision give us? In a word, information.
Erin Allmann Updyke	Yeah.

Erin Welsh	For those animals that have evolved color vision, whether that's trichromacy like most humans, dichromacy like some humans, tetrachromacy also like some humans, being able to distinguish among colors gives them valuable information that they can use to help them, for example, evaluate a mate, forage for food, navigate, or identify predators or poisons. Initially when color vision first arose maybe 500 million years ago, it provided constancy in vision, the ability to sense borders around different shapes, being able to track that this dark red blob was the same dark red blob in shade as it was in sun. Like is this thing a thing or is it just part of the background, if that makes sense? Because if you cannot distinguish among colors whatsoever, just light and darkness, and something that is dark moves into dark, how can you sense it against the background? And so this ability to see color, to distinguish among not just the light and dark but also colors, would have been helpful for the animals living in shallow waters that had to deal with a lot of shifting light and shadows. So skipping ahead millions of years from that 500 million years ago-
Erin Allmann Updyke	Okay.
Erin Welsh	The first mammals were thought to be nocturnal which helped them to avoid predators. So color vision wasn't as helpful in dim light. And so some researchers think that these early mammals lost this full color vision from their ancestors. And then the "re-evolution" quote unquote of color vision occurred as some mammals shifted to diurnal life.
Erin Allmann Updyke	Interesting.
Erin Welsh	Yeah. And the true story is probably much more complicated and complex than this but as color vision continued to evolve in different animal groups, it's unlikely that the same one thing drove its development or refinement over those millions of years. Color vision was selected for within a species or a group of animals because it helped out on multiple fronts. And the utility of trichromatic color vision today, for instance help with foraging, doesn't necessarily mean that foraging was a driver.
Erin Allmann Updyke	Yeah, yeah, yeah.
Erin Welsh	Going into what those possible drivers are for different animal species or different animal groups is just a teeny tiny bit outside of the scope for this particular episode. I mean like there are textbooks about this.
Erin Allmann Updyke	Yeah.
Erin Welsh	But for anyone who wants to learn more, I will direct you to the incredible book 'An Immense World' by Ed Yong which was featured as one of the TPWKY book series books. And there's a fantastic chapter in 'An Immense World', although all the chapters are fantastic, on color vision in the animal world. But for the purposes of this episode, I'm just going to stick with what we know or what we hypothesize about color vision in primates. And last season in our venomous snakes episode, I talked about the snake detection hypothesis which deals with many aspects of primate vision, not just color. But today I'm just going to be talking about color vision and how that came about in primates as opposed to like long distance, acuity, forward facing eyes, stuff like that.

	Between 29-43 million years ago, something pretty major happened for a particular group of primates. These primates were dichromats, so they had just two cones and they experienced the world in shades of blues and yellows. Until one day for one lineage, a gene was duplicated. This happened to be the long opsin gene. And over time one of those copies of the gene stayed the same while the other accumulated mutations slightly here and there, shifting so that it changed from the long opsin gene to the medium opsin gene.
Erin Allmann Updyke	Hey yeah.
Erin Welsh	To these primates, which were the ancestors of old world primates, the world was no longer just blues and yellows. Now there were also reds and greens. What did these additional colors do for them? One of the major hypotheses is that this new gene allowed these primates to detect red or orange or yellow fruits or new reddish/purplish early leaves, also a good food source, against the green backdrop of foliage, not only helping them to find the fruit but also tell when it was ripe. Why is ripe fruit often red? Probably evolved to help with seed dispersal. So the fruit would turn red when it was ripe, when the fruit was at its sugariest and when the seeds were well developed for survival. It's a two way street at least for information. If color is used as information, something has to be producing that information for a reason and something else has to be receiving and processing that information.
Erin Allmann Updyke	That is wild.
Erin Welsh	Right?
Erin Allmann Updyke	Yeah.
Erin Welsh	I don't know why it like hadn't occurred to me.
Erin Allmann Updyke	Yeah. I remember talking a lot about this hypothesis in that Evolution of Human Health class way back when but never did we talk or did I think about the plant side of it.
Erin Welsh	Right. And I know that results studies are mixed or at least like opinions are mixed as per usual. But I think in general it's easy to just think of colors as existing statically.
Erin Allmann Updyke	Right.
Erin Welsh	That is how they are, that is what has happened especially for things that we interact with frequently. Like we can study plumage in birds and stuff like that but also when we study plumage in birds, we're not seeing what the birds see.
Erin Allmann Updyke	I mean it's the same with like colors of flowers compared to what bees see or what birds see.
Erin Welsh	Right. Or like a coral reef looks completely different to a fish.
Erin Allmann Updyke	A fish.
Erin Welsh	Yeah.
Erin Allmann Updyke	Oh my goodness.

Erin Welsh	I know. This is why we were like struggling with this episode because it's so easy to fall down so many rabbit holes.
Erin Allmann Updyke	Oh my gosh, you guys, this episode was the hardest one I've ever researched.
Erin Welsh	Yeah. It was a tough read for sure. I felt like I had to relearn a lot of things that I had or learn them for the first time.
Erin Allmann Updyke	Well tell me what you learned.
Erin Welsh	Okay. So information, two way street at least.
Erin Allmann Updyke	Okay.
Erin Welsh	But getting back to the foraging thing, researchers have tested this foraging hypothesis in primates with mixed results. Sometimes trichromats are better at finding fruit, sometimes there's no difference between trichromats and dichromats, and sometimes dichromats outperform trichromats. But I want to read you a quote about one person's experience foraging for fruit who had a red-green color vision deficiency.
Erin Allmann Updyke	Okay.
Erin Welsh	Quote: "He observed also that when young, other children could discern cherries on a tree by some pretended difference of color, though he could only distinguish them from the leaves by their difference of size and shape. He observed also that by means of this difference of color, they could see the cherries at a greater distance than he could, though he could see other objects at as great a distance as they." Endquote.
Erin Allmann Updyke	Interesting.
Erin Welsh	Isn't that kind of cool?
Erin Allmann Updyke	Yeah.
Erin Welsh	So there's another hypothesis as to why red-green distinction may have helped us. And I think I'm not entirely sure but I got the sense that it has fallen out of favor.
Erin Allmann Updyke	Okay.
Erin Welsh	And that is that trichromacy evolved in primates as a way to help individuals of the same species communicate with one another. So you know those Japanese macaques, like the ones you see pictures of where they're relaxing in hot springs? Trichromacy may have helped species like them to evaluate mate quality or competition or aggression based on like the redness of their faces. And for other species, it could have been like the shade of the pelt. But the big question for this would be did trichromacy evolve to help them distinguish red traits in other individuals of the same species or did those red traits evolve once trichromacy evolved?
Erin Allmann Updyke	Right, chicken or egg, which came first?

Erin Welsh	Yeah. And it turns out to answer this chicken and egg question, phylogenetics studies suggest that it's the latter, that these red traits became more pronounced once trichromacy already existed.
Erin Allmann Updyke	Interesting. Okay.
Erin Welsh	Yeah. Predator detection is yet another hypothesis, one that I touched on in our snake episode, and there are studies suggesting that trichromats are faster and more accurate when it comes to detecting predators than dichromats. Full color vision would have helped primates to distinguish a leopard from a green background with dappled light, for instance. Studies today evaluating differences in foraging, predator detection, and social group dynamics have found support as well as a lack of support for each of these hypotheses. And in general, we can't reliably say what the primary evolutionary driver of a particular trait was based on how it's used today. Because it's not possible to say with certainty whether that trait, color vision, evolved because of something like foraging or if it was later co-opted or exploited by that thing, if that makes sense.
Erin Allmann Updyke	Right.
Erin Welsh	Throwing a wrench into this evolutionary story is that trichromatic color vision evolved independently in both old and new world primates but in different ways.
Erin Allmann Updyke	Stop it.
Erin Welsh	Right? It's fascinating, let's get into it.
Erin Allmann Updyke	Okay.
Erin Welsh	So that was just like this brief tour of the evolutionary history and possible drivers of trichromatic color vision among old world primates, nearly all of which have this kind of color vision, all a result from that gene duplication event with seemingly little variation.
Erin Allmann Updyke	Okay.
Erin Welsh	On the other hand, new world primates are just a quote "cornucopia" of variation in color vision, as one paper described it.
Erin Allmann Updyke	Cool, I love that.
Erin Welsh	And instead of that gene duplication, I have an asterisk here, this is an exception, color vision in new world primates is determined by variations in that original gene. So there wasn't a duplicated gene, they are just different versions of it. And since this gene sits on the X chromosome, males within a new world species have dichromacy whereas most but not all females have trichromacy.
Erin Allmann Updyke	Oh okay. I had read that and I was like I don't understand. And I just moved on. So fascinating.
Erin Welsh	I did that a lot for human color vision. Yeah.
Erin Allmann Updyke	That's why females. Okay.

Erin Welsh	And to make it even cooler, the different forms of this gene also means that there are different forms of dichromacy and trichromacy depending on which versions of the gene are inherited.
Erin Allmann Updyke	Wow.
Erin Welsh	The exception to this, the little asterisk that I mentioned in new world monkeys are the howler monkeys who have the duplicated gene.
Erin Allmann Updyke	What?
Erin Welsh	So nearly all members of that species are trichromatic.
Erin Allmann Updyke	What?
Erin Welsh	Right?
Erin Allmann Updyke	Oh this is cool, Erin.
Erin Welsh	Isn't that really cool?
Erin Allmann Updyke	Yeah.
Erin Welsh	I also will say that I found in papers, and I'm not sure how well this is studied, but I was curious about whether we have found similar rates or the existence of, period, color vision deficiencies in like old world apes and primates similar to the ways that we see it in humans or the frequencies that we see in humans. And it appears that we actually don't, that humans seem to be the exception to this where we have a fairly high, I know you'll talk about it, rate of color vision deficiencies.
Erin Allmann Updyke	What?
Erin Welsh	And so I don't know why that is and there aren't any hypotheses that I found or explored but I just thought that was an interesting little side note.
Erin Allmann Updyke	Wow.
Erin Welsh	Yeah, yeah. But I think in general what I wanted to do in this sort of evolutionary section was to highlight just how much variation there is in color vision in primates alone.
Erin Allmann Updyke	Right.
Erin Welsh	Not to mention the rest of the animal kingdom.
Erin Allmann Updyke	My goodness.
Erin Welsh	And this is a point that Ed Yong makes in his book that I just absolutely loved and like continued to take to heart, which is that color vision or any sensory information or sensory structure or physiology, it's not something to be ranked in terms of what is better. Oh well dogs have better noses or senses of smell. Like that is not a very useful metric or way to try to understand what another animal or another human or whatever experiences.

Erin Allmann Updyke	Right.
Erin Welsh	So anyway, monochromacy, dichromacy, trichromacy, tetrachromacy and beyond, all of these different types of color vision have evolved and have been selected for to help with gathering information. We're not more advanced because we have trichromatic color vision, it's just more complicated than that. And being able to distinguish among colors isn't always for the better. And there are tradeoffs associated with the evolution of trichromatic color vision. An animal can only take in and process so much sensory information, you can't max out all the boxes. And the least useful sensory feature is usually the first to go.
	In the case of trichromatic primates, the evolution of trichromacy seems to have coincided with the loss of genes that are associated with chemical sensing via smell, probably for pheromones. And so when primates evolved red-green color vision, they lessened their reliance on this other form of chemical information. And so I think, again, this is just to say that we have a tendency to place humans at the pinnacle of evolutionary achievement without considering the benefit of other strategies. And this failure of imagination has led us to make some pretty big assumptions about other animals, like how we talked about earlier how we thought that fish didn't see color for decades or dogs couldn't see color at all. And it has also led us to create a world where it can be difficult to navigate if you don't have full color vision.
Erin Allmann Updyke	Right.
Erin Welsh	Which brings me to the other part of this history section. The 'how did we learn about color vision deficiency in humans' part. Of course I have to begin with a quote, and Erin bear with me, it is probably the longest quote I have ever read outside of like a firsthand account.
Erin Allmann Updyke	Oh okay.
Erin Welsh	But it's worth it, I swear.
Erin Allmann Updyke	Okay.
Erin Welsh	All right, get ready. Quote:
	"It has been observed that our ideas of colors, sounds, taste, etc, excited by the same object may be very different in themselves without our being aware of it. And that we may nevertheless converse intelligently concerning such objects as if we were certain the impressions made by them on our minds were exactly similar. I was always of opinion, though I might not often mention it, that several colors were injudiciously named. The term pink, in reference to the flower of that name, seemed proper enough. But when the term red was substituted for pink, I thought it highly improper, it should have been blue in my apprehension as pink and blue appear to me very nearly allied, whilst pink and red have scarcely any relation. Since the year 1790, the occasional study of botany obliged me to attend more to colors than before. With respect to colors that were white, yellow, or green, I readily ascended to the appropriate term. Blue, purple, pink, and crimson appeared rather less distinguishable, being according to my idea, all referable to blue.

	I was never convinced of a peculiarity in my vision until I accidentally observed the color of the Geranium zonale by candlelight in the autumn of 1792. The flower was pink but it appeared to me almost an exact sky blue by day. In candlelight however it was astonishingly changed, not having then any blue in it but being what I called red, a color which forms a striking contrast to blue. I requested some of my friends to observe the phenomenon when I was surprised to find they all agreed that the color was not materially different from what it was by daylight except to my brother, who saw it in the same light as myself. This observation clearly proved that my vision was not like that of other persons and at the same time that the difference between daylight and candlelight on some colors was indefinitely more perceptible to me than to others."
Erin Allmann Updyke	I love that so much, Erin.
Erin Welsh	Right? Do you see why I had to do the whole thing?
Erin Allmann Updyke	100%. Yes.
Erin Welsh	Okay, good. I was like gosh, this is really long as I'm reading it.
Erin Allmann Updyke	But it's so good because also, do you know what that tells you? He's using his rods that we ignored.
Erin Welsh	Yes, yes. I know.
Erin Allmann Updyke	Rods become more important when you don't have as many cones.
Erin Welsh	Yes. It is so interesting, I loved it so much. And it's really important for a number of reasons. But first that quote was from John Dalton in his 1794 treatise titled 'Extraordinary Facts Relating to the Vision of Colors'. And it's great for a few reasons, right. Number one, it's just such a great like systematic retelling of his thought process, of exactly when he realized, how he realized.
Erin Allmann Updyke	Yeah.
Erin Welsh	Like everything about it. And number two, he mentioned his brother also experiences this.
Erin Allmann Updyke	So good.
Erin Welsh	Which is really good, really interesting. And number three, it is as far as we know the first scientific description of color vision deficiency.
Erin Allmann Updyke	Wow.
Erin Welsh	In honor of his observation, color vision deficiency was and sometimes still is called Daltonism. But 1794.
Erin Allmann Updyke	Wow.
Erin Welsh	Like doesn't that seem recent?
Erin Allmann Updyke	I don't know how to gauge it, Erin.

Erin Welsh	I know, I know. I mean I fully expected to find like a long list of historical accounts going back hundreds or maybe even thousands of years hinting at color vision deficiency. But no. And I will say that like there are mentions of confusion in color vision that were... Like it seemed fairly well known about or at least enough so for like King George III to make some comment about it at a dinner in 1785. Like some people have an ear for music, some people don't, some people have an eye for colors, some people don't. That kind of thing. And there was also a reference to it in a German medical science magazine and also other scattered references in the 1700s.
	But Dalton really seems to be the first to have written about it scientifically, like with an analytical approach. And I don't know, it does seem recent but at the same time in a way it does make sense considering that color doesn't seem subjective, it seems like inherent properties of objects. You learn your colors at an early age. If you confuse colors, it's an easier leap to think that there's something wrong with your vision in terms of acuity, like your sight, rather than your perception. And like I kind of already mentioned, as a species in general we're not great at imagining the world as it might be perceived by other species, let alone other humans, I feel like sometimes.
Erin Allmann Updyke	So true.
Erin Welsh	And so it would take a really keen observer to question whether color is truly objective and then also have the opportunity to publish those observations.
Erin Allmann Updyke	Yeah, yeah.
Erin Welsh	It happened when it happened. And when it happened, Dalton hypothesized in this treatise that his and his brother's color vision deficiency was caused by the vitreous humor of their eyes being tinted blue, making it absorb longer wavelengths. Yeah. He requested that after his death, his eyes be tested to confirm his hypothesis. And so the day after he died, July 28, 1844, that's exactly what was done.
Erin Allmann Updyke	What?
Erin Welsh	Only the person performing at this autopsy found no support for Dalton's hypothesis. The vitreous humor, not tinted.
Erin Allmann Updyke	I don't have the slightest idea how you would even do that test. Wow.
Erin Welsh	I'll include the paper that that mentions this, it goes into more detail about it.
Erin Allmann Updyke	Okay, okay, okay. Cool.
Erin Welsh	The alternative hypothesis was that it came from a cerebral anomaly, like the part of your brain that perceives color was somehow different but that also didn't hold up.
Erin Allmann Updyke	Yeah.
Erin Welsh	The explanation that is generally accepted today for most cases of color vision deficiency was actually first proposed in 1781 by a mysterious person named Giros von Gentilly. Apparently no one knows anything about who this person actually was or whether that was like a real name or just a pen name.

Erin Allmann Updyke	What?
Erin Welsh	Yeah, he's called like an obscure mysterious figure.
Erin Allmann Updyke	Whoa.
Erin Welsh	Yeah.
Erin Allmann Updyke	I hope someone calls me that someday.
Erin Welsh	Obscure and mysterious? That's hilarious. And so this von Gentilly guy wrote in that German science magazine that I had mentioned that he thought that color vision deficiency occurred if one or two of the three kinds of quote unquote "molecules or membranes in the retina was not functional, either paralyzed or constitutionally overactive".
Erin Allmann Updyke	It's interesting that they seem to have known that there were like three things involved.
Erin Welsh	Yeah. Well okay, and so this is one of the areas that I did not get into which is like Newton and color theory.
Erin Allmann Updyke	Oh my gosh.
Erin Welsh	And light spectrum. You know, like all of that. And I was just like I don't know how to even begin to-
Erin Allmann Updyke	Do it?
Erin Welsh	Talk about that.
Erin Allmann Updyke	Yeah.
Erin Welsh	Yeah. And so I wonder whether that coincided with sort of the development of some of those ideas around what color, what the visible spectrum of light is.
Erin Allmann Updyke	Okay, okay. That makes sense.
Erin Welsh	And so like how many colors do you need to combine in order to make all the colors that we see?
Erin Allmann Updyke	Right, right, right. Okay. Yeah.
Erin Welsh	Yeah. I don't know, that's my guess.
Erin Allmann Updyke	Yeah.

Erin Welsh	And so then after this von Gentilly, it's unclear whether his idea gained traction then or we just only know about it in retrospect, but it's possible that British polymath Thomas Young stumbled across it. And like Thomas Young did one bajillion things. He proposed the wave theory of light, he helped to translate the Rosetta Stone, he also... Right? He also further developed this hypothesis about color perception, suggesting that it was due to the presence of three kinds of nerve fibers in the retina.
Erin Allmann Updyke	Okay, okay.
Erin Welsh	Yeah. And over time this framework for how color vision worked via cones and rods was refined with anatomical studies, molecular studies, advancements in physics, and there's just the growth of the field of vision science. And in the 1990s, the nature of Dalton's color vision deficiency was finally made clear when the Manchester Literary and Philosophical Society granted permission to a few scientists to run some tests on the remnants of Dalton's eyeballs.
Erin Allmann Updyke	Oh my goodness.
Erin Welsh	Right? How amazing. I'd be so worried to drop that little tube. I'd be like oh god. But they confirmed that Dalton lacked the middle photopigment cone cell, making him a deuteranope.
Erin Allmann Updyke	Wow.
Erin Welsh	Case closed. Yeah.
Erin Allmann Updyke	Love it.
Erin Welsh	Dalton may not have been the first person to notice that the way he saw colors was not the same as most other people. I mean he was definitely not the first, we've kind of established that. But his careful scientific analysis of what he suspected was going on caught the attention of other scientists. And for years color vision deficiency was seen as kind of an anomaly, just this like curious thing that some people had that some people were born with or acquired later in life. And it certainly prompted more research into the structure and function of the eye and how vision worked, as well as philosophical musings over how we are each in our own little world and can never truly experience life from someone else's perspective.
Erin Allmann Updyke	Oh my goodness.
Erin Welsh	But color vision deficiency took on a practical importance starting in the second half of the 1800s, coinciding with the rise of industrial transportation. The so-called golden age of rail travel, growth in maritime travel, and of course automobiles and airplanes. With all of these forms of travel, people had to use certain signals to determine when it was safe to proceed, when to stop, when to proceed with caution, when to back up. And the signaling was done primarily with colors. Suddenly color vision deficiency was not just a medical curiosity but according to one physician in 1880, quote: "Daltonism can be cause of discussions, arguments, battles, industrial and commercial losses, dreadful accidents, and irreparable miseries."
Erin Allmann Updyke	Wow.

Erin Welsh	Yeah. Strong words. And this fear was realized in November 1875 when two express trains on a single track, one heading from Stockholm to Malmö and the other from Malmö to Stockholm collided head first in the middle of the night. Nine people were killed in this collision. And about a year after the accident when they were trying to like figure out what had happened, who was at fault, how can we prevent this from happening again, an ophthalmologist named Frithiof, I don't know how you say it, Holmgren, suggested that either the engineer of the northbound train or his oiler was color deficient and misinterpreted the signals, leading to the crash. Neither of them could be tested because they had both died in the accident but this didn't stop the speculation. And the Lagerlunda collision as it was called has been referenced over and over again as a case study of the tragedies that could result from having someone with color vision deficiency in charge of transportation or in charge of interpreting those signals.
Erin Allmann Updyke	So just to be clear, that was just one guy's idea that this is what happened.
Erin Welsh	Yeah.
Erin Allmann Updyke	But nobody knows for sure.
Erin Welsh	No. So okay, there is a paper from 2012 that goes into-
Erin Allmann Updyke	Okay.
Erin Welsh	It's an incredible in depth analysis of like the different trains, how the lights would have worked. And they did this in depth like super detailed examination of this crash and they concluded that even if color deficiency was a factor, which it's not clear that it was at all, it was far from being the only factor responsible and probably there was some sort of like problem with one of the trains themselves.
Erin Allmann Updyke	Okay.
Erin Welsh	But despite this, yeah, this was like a real catalyst.
Erin Allmann Updyke	Wow.
Erin Welsh	The Lagerlunda collision, you'll find it in so many references to anything related to color vision deficiency in industry and regulations. It was this huge catalyst for the introduction of color vision screening and restrictions on what jobs in the transport industry that people with color vision deficiency could hold. And most of the time it was just like nope, sorry, we have to perform these tests beforehand.
Erin Allmann Updyke	Yeah.
Erin Welsh	I think that's... I'm not an expert in anything related to industry and transportation and stuff like that but it just seems like another solution could be to change the signals. Right? I don't know, maybe that's a very naive thing to say but I don't know.
Erin Allmann Updyke	I mean, someone tell us otherwise.
Erin Welsh	Yeah, like maybe there's... I don't know.
Erin Allmann Updyke	Yeah.

Erin Welsh	But yeah, this was like a really formative moment and one of the things that they used to test people who were applying for these jobs was the Holmgren, named after that guy, wool strands test, where you had to match wool of different colors. And I actually couldn't get a very good sense of how many train or maritime or aviation accidents were definitively attributed to someone misreading the signals due to color vision deficiency.
Erin Allmann Updyke	Okay.
Erin Welsh	I think it did happen, like I think there are at least a few confirmed cases of that happening. But even the ones where it was just pure speculation absolutely captured the public's imagination and fear and led to these regulations being quite strict for a very long time. And only recently have some of these restrictions become a little more relaxed or more specific. And part of that is a result of us learning more about the different types of color vision deficiency and being able to test for those differences, using for instance those Ishihara tests, which I'm sure many of you are familiar with where's that circle of bubbles and some of the bubbles are a different color and they make up the shape of a number and if you can determine what that number is, then you don't have color vision deficiency of that particular kind or something to that effect.
Erin Allmann Updyke	I just made my toddler take that test.
Erin Welsh	I've taken that test a number of times.
Erin Allmann Updyke	Me too. I took it at the same time.
Erin Welsh	But anyway, since color vision was first put out there into the scientific world, we've come a really long way towards understanding the mechanisms and genetics of color vision. And we finally, I think at least in small ways, have started to move away from exclusionary practices like limiting what professions you can have and making an effort to be more inclusive, recognizing that we may not all experience the world in the same exact way. And maybe that means something like a package in R that gives you a color palette for figures that's quote unquote "colorblind safe". Or maybe that means changing the types of signals used in transport so that people who have color vision deficiency can still utilize those signals. Or maybe that means creating glasses or other methods to allow us to distinguish a wider spectrum of colors. So Erin, a little bit of an abrupt transition. But what can you tell me about these glasses and other aspects of color vision deficiency today?
Erin Allmann Updyke	I can do my best to tell you something right after this break.
TPWKY	(transition theme)
Erin Allmann Updyke	Pretty much every single paper that I read cites that when it comes to congenital color vision deficiency, which again is what we're focusing on, the prevalence overall is 8% in males and 0.5% in females.
Erin Welsh	I saw those numbers over and over again and I wasn't even looking for them.
Erin Allmann Updyke	Over and over and over and over and over. I have no idea where these numbers came from, I don't know if they're real. I mean I guess they're real because they're in every single paper. One paper that I read said that this is true in people of Northern European descent but it varies across the globe. But I couldn't find data like comparing different regions. But yeah, that's the numbers that I have.

Erin Welsh	Okay.
Erin Allmann Updyke	Red-green color vision deficiencies, of course far more common overall. Interestingly the deuteranomalies and deuteranopia are more common than protanomaly and protanopia. I don't know why. And then I don't even have numbers for things like the monochromacies or tritanomaly because they're just that rare. So that's epidemiology. I mean it's pretty straightforward.
Erin Welsh	Okay. I don't know what I expected. But yeah.
Erin Allmann Updyke	There it is.
Erin Welsh	There it is.
Erin Allmann Updyke	It just means we can spend some more time talking about like what's being done or what research are people doing or whatever.
Erin Welsh	These glasses, Erin. I have to know like what do they do? You see these amazing videos and then I'm like is the hype real? And it doesn't work for some people, how does it work? Why doesn't it work?
Erin Allmann Updyke	Yeah.
Erin Welsh	Why does it work?
Erin Allmann Updyke	So I guess which glasses are you thinking about? Like the EnChroma glasses?
Erin Welsh	I suppose any of them, yeah.
Erin Allmann Updyke	So yeah, let's talk about it. There exist things like tinted lenses that are just literally tinted lenses that you can wear over one eye or both eyes that in some studies help some people with some kinds of color vision deficiencies. There are other like these lens filter type things which come in the form of glasses commonly called EnChroma filters. They have a lot of theoretical usefulness because what they do, which is fascinating and way above my head, is that they modify the perceived wavelength of light. So something, Erin, like your red sweatshirt that you're wearing, the wavelength of light that's coming off of that into my eyes with this filter would be shifted such that if my cones are also shifted, I might better be able to distinguish it as red. I guess.
Erin Welsh	Okay. Yeah.
Erin Allmann Updyke	But in the papers that I read at least, there's pretty limited evidence of their actual effect in terms of color discrimination. In general, at least in the papers that I read, both the tinted glasses as well as these various types of filter lens glasses as well as some experiment contact lenses, which is interesting, can show some increases in color perception and contrast enhancement in nature, like when given natural scenes to look at, but they haven't yet shown to make it to the level of like someone being able to pass an Ishihara test who couldn't before.
Erin Welsh	Okay.

Erin Allmann Updyke	At least from what I read. Yeah.
Erin Welsh	That's very interesting.
Erin Allmann Updyke	Now even more interesting or I think even more interesting is that it is also theoretically at least possible to try and treat color vision deficiency with gene therapy, given that most of the time what we talked about today are genetic disorders.
Erin Welsh	Yeah.
Erin Allmann Updyke	But there are a lot of possible individual gene mutations. But it's also maybe not necessary to correct the exact gene mutation in order to restore typical trichromatic color vision, right. Because all you would have to do is restore a fully functional opsin gene, for example, with the expected sensitivity, right, an M opsin if you're missing that one or an L opsin if you're missing that one, right. But it's a lot more complicated than that. I will say that a number of studies have done this in mice as well as in some primates. And they have shown that they can induce some trichromatic color vision in mice and in primates that are missing it.
Erin Welsh	Okay.
Erin Allmann Updyke	So it's possible, at least the theory is solid, we've done it in animals. But what's really interesting and I think one of the things that makes the idea of gene therapy really interesting is that not only does it beg the questions around like the neural plasticity like we talked about, can you restore trichromatic color vision in someone whose eyes developed during embryo development with only two sets of cones? Can they still then be restored? Because the cone cells are involved in, again, a lot more than just color vision. So can we quote "fix" these deficiencies by adding back those genes after this period of development when these complex neural circuits are being formed?
Erin Welsh	Interesting. Okay, yeah.
Erin Allmann Updyke	So we can do it in animals at least in a couple of studies but we still don't know if it's possible in humans.
Erin Welsh	Interesting.
Erin Allmann Updyke	Yeah.
Erin Welsh	Gene therapy.
Erin Allmann Updyke	Gene therapy.
Erin Welsh	I always love when we talk about it and then I'm always like this is a big thing.
Erin Allmann Updyke	It is a big thing especially-
Erin Welsh	With a lot of implications and complications and question marks.
Erin Allmann Updyke	Exactly. Yeah, I love it. But that, Erin, is color vision deficiencies and literally everything I know about them.

Erin Welsh	You know I think that as difficult as it felt sometimes to kind of like hone in on what we wanted to talk about, I really feel like this was a great one to do and I learned so much about color vision deficiency.
Erin Allmann Updyke	Same, same.
Erin Welsh	Yeah.
Erin Allmann Updyke	And about just like color vision in general. I love it.
Erin Welsh	Yeah. And if listeners, you have favorite color vision facts about animals or about humans or about anything, send them our way.
Erin Allmann Updyke	I want to know them. Yeah.
Erin Welsh	Speaking of learning more and knowing more, I have many things to shout out today. First I'm going to shout out some of the resources that I used for this, just a few of them because there were a lot. On the evolutionary side of things there are so many papers by a really prominent researcher in the field, Gerald Jacobs, about the evolution of color vision in primates and animals in general. There is also a great paper called 'The Causes and Consequences of Color Vision' by Gerl and Morris from 2008. And for the history of color blindness itself, there's a book called 'The History of Color Blindness' by Philippe Lanthony.
	And I did not mention this at all, I completely forgot to mention this or include this in my notes, but one of the really interesting things that I came across was the discussion of color vision deficiency in art. And so being able to look at like art history and different art movements and detecting what artists may have had color vision deficiency based on how they represented the world in the context of whatever art movement was popular at the time. So if it was like during the time when people were painting literally the world as they perceived it, then you might be able to tell more than if it was at a time when it was more, I don't know, up in the air.
Erin Allmann Updyke	Abstract.
Erin Welsh	I don't know anything about art history. Yeah. Abstract, impressionist, who knows? But that is like really cool, so there's a paper by Marmor and Lanthony from 2001 called 'The Dilemma of Color Deficiency and Art'. And on that note, further reading, 'An Immense World' by Ed Yang, I'll shout it out again, it's phenomenal, it'll change the way you perceive the world. And then there are two books that I did not read for this. One is called 'The Island of the Colour-blind' by Oliver Sacks, and this is about a group of people that have achromatopsia. And then there is a book that I read years ago called 'Through the Language Glass: Why The World Looks Different in Other Languages' by Guy Deutscher. And there is a chapter in this book, at least one, on the evolution of language as it pertains to color terminology that I found fascinating.
Erin Allmann Updyke	I shockingly had less papers for this episode than usual because the papers are incredibly detailed. Shout out to Wikipedia for helping me understand the papers, so shout out there, okay. But the papers that were actually incredibly detailed once I understood them were a 2003 paper from Annual Review of Neuroscience just called 'Color Vision' that was really helpful in understanding how that works. And then a paper from the journal Eye from 2010 called 'Color Vision Deficiency'. Those I think were the two that I used the most heavily. But I have so many more on the biology of this, on the lenses and glasses and gene therapy, on tetrachromacy and all of that. You can find the sources from this episode and every one of our episodes on our website thispodcastwillkillyou.com under the EPISODES tab. Check it out.

Erin Welsh	Thank you again to Kristen for sharing your story with us. We appreciate it so much.
Erin Allmann Updyke	Yeah, we do. Thank you to Bloodmobile for providing the music for this episode and every one of our episodes.
Erin Welsh	Thank you to Lianna Squillace for our amazing audio mixing.
Erin Allmann Updyke	And to Exactly Right network.
Erin Welsh	And to you, listeners. Thank you. We hope that you enjoyed this episode, found it interesting, learned something, have more facts to share, have questions, anything.
Erin Allmann Updyke	And a special shout out to our patrons. Thank you so, so much for your support.
Erin Welsh	Yeah, we really appreciate it. Okay. Until next time, wash your hands.
Erin Allmann Updyke	You filthy animals.