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What is it like to be a tetrachromat?

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Abstract
Most people are trichromats, but some people have an extra kind of cone cell in their retinas: they are tetrachromats. Recent science shows that some tetrachromats can make distinctions between reflectances that ordinary viewers are unable to detect. This paper asks what kind of colour experience these tetrachromats have. It rejects the claim that they simply see finer gradations of those colours familiar to trichromats. Instead, it draws on both scientific evidence and anecdotal data to argue that tetrachromats visual acuity is due to seeing novel colours: elementary colours that trichromatic viewers are unable to see or imagine.

Keywords
Colour · Novel colours · Perception · Vision

Introduction

Most of us are trichromats – we have three different kinds of cone cells, the receptors in the retina sensitive to different wavelengths of light. However, recent research shows that there are some people who have *four* different kinds of cone cells: they are tetrachromats.[1] Tetrachromacy gives some of these people more refined vision than normal human observers – they can make distinctions between visual stimuli that evade trichromats. As philosopher Fiona Macpherson says, they "see colours that normal human trichromats do not." (Macpherson, 2020, p. 188) Science has concerned itself with the physiology, genetics and functionality of tetrachromacy. But it has resisted asking what the colour experience of a tetrachromat is like, and how it differs from that of a human trichromat. Philosophers and scientists have acknowledged the interest of the question – vision scientist Gabriele Jordan observes, "[t]his private perception is what everybody is curious

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1 In fact, ordinary viewers have a fourth kind of cone on the periphery of the retina, with a peak sensitivity of around 538nm – these cells, however, seem to make no contribution to conscious colour vision, and do not give rise to the tetrachromacy that is my focus here. The discovery of this extra-foveal tetrachromacy was presented by M. M. Bongard and M. S. Smirnov in a 1956 paper, 'The Four-Dimensionality of Human Colour Space', reproduced in English translation in (Danilova & Mollon, 2022).

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about" (Greenwood, 2012) – but they generally pass over it, expressing scepticism that there is much to be said about the tetrachromat's visual experience. Philosopher C. L. Hardin, musing on whether the experience of a tetrachromat discovered by Jordan could be radically different from that of ordinary human vision, thinks, "[p]robably not", but regrets that "[n]obody asked the woman about the *quality* of her experience." (Hardin, 2014, p. 386)

Following Macpherson, I take it that there are two ways of understanding what tetrachromat colour experience could be like.[2] First, the enhanced visual acuity of tetrachromats could manifest as an experience of more subtle gradations of colours than trichromats see. So, where a trichromat finds, say, two examples of orange paint indistinguishable, the tetrachromat might experience the one that reflects a slightly longer wavelength of light as slightly yellower than the other. As Macpherson puts it, this option proposes that tetrachromats see "different determinates … of the same shades of colour" that trichromats experience. (Macpherson, 2020, p. 188)[3] That is to say, they see more and finer shades of the colours that trichromats are familiar with. This, I take it, is Hardin's view.

Second – and this is the option that radically departs from ordinary trichromat experience – tetrachromats' enhanced visual acuity could indicate their perception of what I call "novel" colours. Novel colours, to adapt Thomas Nagel's description of the sonar experience of bats, "have a specific subjective character", but are "beyond our ability to conceive" as trichromats. (Nagel, 1974, p. 439)[4] Such novel colours, if they exist, will be elementary colours, not phenomenal composites of other colours (say, unusual tints or shades of familiar colours). They will be as different from the colours that trichromats know as, say, red and green differ from blue and yellow.[5] So, on this option, much as colour-blind people are often thought to see a subset of the colours that trichromats see (Hardin, 1993, pp. 145–146; Viénot et al., 1995)[6], "trichromats see a subset of the colours that the tetrachromat sees." (Macpherson, 2020, p. 187) That is to say, in addition to the colours

[2] There are other possibilities we could consider, and I discuss these in Section 2, but as will be seen there, they are not empirically plausible.

[3] Macpherson draws on Byrne and Hilbert's (2010) analysis of colour-blind experience in articulating this position.

[4] My paper shares with Nagel's a concern for such experiences. Although it is not meant as an endorsement of the anti-reductionist argument he develops there, those partial to Nagel's argument could use my results to similar ends. Jackson (1982) presents just such an argument in a thought experiment involving "Fred", who can see a novel colour (perhaps because his eyes have a fourth kind of cone cell). Jackson uses the thought experiment to set up a version of his famous "knowledge" argument, arguing for the existence of qualia. (Jackson, 1982, pp. 128–130) The concept of novel colours is explored in detail by Thompson (1992). Thompson builds on Jackson's thought experiment, but rejects his conclusion.

[5] My use of "novel colours" differs somewhat from Macpherson's. For Macpherson, novel colours are those that normal trichromat viewers do not, or do not ordinarily see, and these include the fine gradations and radically new colours proposed in both options. (Macpherson, 2020, pp. 176–178, 187)

[6] I discuss this view of colour-blind experience, and address competing views, in Section 2.

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that trichromats are capable of seeing, tetrachromats see further colours, beyond normal human experience – novel colours.[7]

I argue that the correct understanding of the experience of tetrachromats with enhanced visual acuity is to be found in this second, more radical option. Section 1 sketches the relevant elements of visual processing for understanding the topic, including cone cells and their function, opponent processing, and how this physiology shapes visual experience. It then turns to the subject of tetrachromacy, introducing the case of cDa29, the anonymous subject of a study by Gabriele Jordan and colleagues (2010). Section 2 shows that cDa29's enhanced visual acuity is accompanied by experience of at least one novel colour that appears "laid over" the spectrum familiar to trichromats. Section 3 looks at scientific evidence from another research group, led by Kimberly A. Jameson, as well as anecdotal evidence from further tetrachromats. On the face of it, this data contradicts the result of Section 2, suggesting that tetrachromats do not see novel colours, only finer gradations of colours familiar to trichromats. Section 4 resolves this apparent contradiction by drawing on evidence from an earlier study by Jordan's group. This, together with other considerations, leads me to find that tetrachromats with enhanced visual acuity do indeed gain that acuity through an ability to see novel colours. I conclude with some remarks addressing the incredulity that the prospect of novel colours in tetrachromat experience is prone to elicit.

1 Trichromacy and tetrachromacy

Trichromats – normal or ordinary viewers as a I shall sometimes call them – have three different kinds of cone cells in their retinas. These are sometimes called red, green, and blue cones, as these colours roughly indicate the wavelengths of light where their peak sensitivities lie. But as the cones are not directly associated with colour experience, they are now more often named to indicate the wavelengths they are responsive to: S (Short), M (Medium), and L (Long). Computer, smartphone and TV screens are designed to excite these cell types. Using very limited stimuli – light from red, green and blue pixels – they produce all the colours that trichromats are familiar with. The cones are the first stage in colour vision. It is now widely thought that there are two further stages of processing, in which colour information is encoded in different ways. The next stage, opponent processing, describes how information about colour is encoded as it leaves the retina and enters the brain. Opponent processing takes input from the cones and codes it in a new form in three channels: one for blue and yellow, another for red and green, and a

[7] Another possibility is that tetrachromats see *entirely* different colours to those trichromats that see – i.e., all their colours could be novel. I will elaborate on this possibility at the end of Section 2.

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third for black and white.[8] Each of these channels acts like an on-off switch: active, it represents one colour, and inactive, it represents the other of its opponent pair. Opponent processing does much to shape our visual phenomenology – the colours it encodes – red, green, blue, yellow, black and white – have often been considered the elementary colours of visual experience. All other colours, on this account, are combinations of these. (Hering, 1964, p. 42) The "on-off" character of opponent processes also explains why we never (or rarely, perhaps) see reddish greens and yellowish blues, and why combinations of the other colours – blue-reds (i.e., purples), blue-greens, yellow-reds (i.e., oranges), and yellow-greens – are a familiar part of ordinary visual experience.[9]

Much less is known about the third stage of colour processing, which occurs in the visual cortex, especially within the area known to vision scientists as V4. (Zeki, 1980) Although opponent processing plays a prominent role in shaping our colour experience, the colours that it encodes do not wholly accord with colours as we experience them. Information about colour constancy, illumination, surface colour and transparency, for example, transform and complicate our experience of colours, and it is clear that this information cannot be encoded in the simple form supported by opponent processing. Indeed, opponent processing at the early stage of visual processing does not even accurately encode Hering's elementary colours as we experience them. As John Mollon and Jordan observe, "most color scientists are agreed that the chromatically opponent cells of the early visual system … do not correspond colorimetrically to red–green and yellow–blue processes." (Mollon & Jordan, 1997, p. 382) According to Arne Valberg, opponent processing cells at this early stage are "not the correlate for seeing a particular hue quality, say unique [i.e., elementary] red. This latter correlate, if it exists as a separable entity, must be associated with yet unidentified, higher-level neural activities." (Valberg, 2001, p. 1645)[10] Why are the second and third stages important to my enquiry? It is not enough for colour vision that a subject's retina has certain kinds of cone cells. These must also be wired appropriately into the visual system. That requires encoding information into opponent processing, which mediates between the eye and visual cortex, and, deeper in the visual cortex, encoding information into another form again that aligns with visual experience and makes it available to varying kinds of cognition.

Vision varies in complex ways in the animal kingdom, and normal human vision is far from being standard. Many animals, including small fish and most birds, are tetrachromats – they have a fourth kind of cone that detects light in the ul-

[8] In dark, or "scotopic", conditions, the cones become inactive, and another class of photoreceptors, the rod cells, feed into the black–white channel. In low or "mesopic" light, both cones and rods are active. (Cao et al., 2008)

[9] For an account of seeing yellowish blues, see (Newall, 2021).

[10] A survey of efforts to locate and characterise this correlate is given by Kuehni (2014, p. 284).

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traviolet range. (Chen et al., 1984; Marshall & Arikawa, 2014)[11] For some time it has been hypothesised that there are people who could be tetrachromats, having a fourth kind of foveal cone photoreceptor sensitive to light in the ordinary visible range.[12] The possibility was first raised by Hessel (De Vries, 1948). He noted that some colour-deficient males have a mutant version of the M or L cone with a different wavelength sensitivity to ordinary M or L cones. The daughters of these men could inherit the mutant cone from their fathers, *and* the normal cones from their mothers. They would thus have S, M and L cones, *and* the mutant version of the M or L cone, giving them in total *four* kinds of cones, each with a different wavelength sensitivity. The development of M and L cells is coded in X chromosomes, and since it is largely women who inherit two sets of X chromosomes – one from their mother and one from their father – it is largely women who develop tetrachromacy in this way. This, de Vries suggested, could impart some form of enhanced vision. Jordan and Mollon (1993) revisited this study, following up de Vries' suggestion, but described their results as inconclusive. More recent work, by Jordan and colleagues (2010), announced a dramatically different result. Jordan and her colleagues studied 24 women with a fourth cone. Again, most showed no unambiguous evidence of being able to use the extra cone to enhance vision. But one subject, called "cDa29" in the paper, convincingly passed the researchers' tests, consistently and clearly making visual distinctions unavailable to trichromats. "[T]here is no doubt that she [cDa29] is the real deal", Jordan says. (Higgins, 2022)

Before discussing these tests, it will help to say something about how an extra receptor in the retina can be used by the visual system. Jordan and her collaborators are very aware of this problem: "does her visual system have enough plasticity to take advantage of the input from an extra class of cone?" they ask. (Jordan et al., 2010, p. 1) In order to function as part of the visual system, these cones would presumably need to feed into a new opponent processing channel (or more than one), and would also require the visual cortex to adapt so that it could process signals from this new channel or channels. That may seem improbable, but two striking studies suggest that visual systems can adapt in exactly this way. One describes mice genetically engineered to express a human gene for L cones, gaining a new ability to discriminate between long wavelengths. (Jacobs et al., 2007) The other describes the transformation of two naturally dichromat adult squirrel monkeys, Dalton and Sam, into trichromats.[13] This was achieved through virally-mediated gene therapy, involving injections into the retina. The monkeys developed L cones, and after five months they become functional, allowing the monkeys to distinguish

[11] Some animals have even more kinds of colour photoreceptors. For example, mantis shrimp have twelve – although, curiously, this does not give them excellent colour vision. (Thoen et al., 2014)

[12] The idea has a history in science fiction too. Olaf Stapledon's *Odd John* , originally published in 1935, includes a character, Jelli, with "hypersensitive vision" who can "distinguish two primary colours within the spectrum-band we call blue". (Stapledon, 2012, p. 166)

[13] Male squirrel monkeys are dichromats. However, two-thirds of females naturally develop trichromatic vision. (Jordan & Mollon, 1993, p. 1496)

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red and green stimuli. (Mancuso et al., 2009) According to Jay Neitz, one of the lead researchers, “we knew right away when it began to work. It was if they woke up and saw these new colours. The treated animals unquestionably responded to colours that had been invisible to them.”[14] (Pastor, 2009) These two studies point to the remarkable plasticity of the visual system in responding to input from novel sensory receptors – and suggest that it might also be possible for humans to make use of a fourth cone.[15]

What led Jordan and colleagues (2010) to conclude that cDa29 could make use of a fourth cone? First, genetic tests showed that cDa29 carries the genes for the three trichromat cones and a fourth mutant cone (Jordan et al., 2010, p. 10), and that in addition to the S cones, she has “three well-spaced photopigments in the long-wave spectral region” where ordinary subjects have only two (the M and L cones). (Jordan et al., 2010, p. 16) In order to show that cDa29 can make use of these cones, her visual abilities were investigated using two kinds of tests. The first involved presenting combinations of red (670nm) and green (546nm) lights that to a normal viewer appear to match an orange light (i.e., circa 590nm). cDa29 could not match an orange stimulus with any combination of red and green lights – something trichromats can always do. (Jordan et al., 2010, p. 16) Second, cDa29 could reliably distinguish orange wavelengths of light (around 590nm) from particular combinations of red (670nm) and green (546nm) that trichromats find impossible to distinguish. (Jordan et al., 2010, p. 16) Both tests indicate cDa29’s ability to make visual distinctions impossible to normal viewers (since refusing a match between two stimuli, as in the first test, entails the capacity to make a distinction between the two). cDa29 is thus what we may call a functional tetrachromat: she possesses four kinds of cones, and she can also make use of them.[16] When I speak of what it is like to be a tetrachromat, I mean the colour experience of functional tetrachromacy.

[14] Note that my argument in this paragraph does not require that the monkeys actually experience red and green. It is only meant to show that it is possible for the visual system to adapt so that one can make use of new colour receptors. But I will employ the idea that they could experience red and green later.

[15] These studies also indicate the route of evolution of red–green colour vision where it occurs naturally in mammals. Functional red–green vision was likely first triggered by M cones mutating into L cones, and did not need to be immediately accompanied by complementary evolution of the visual system: “Additional genetic changes that refine the downstream neural circuitry to more efficiently extract sensory information could then follow over many generations.” (Jacobs et al., 2007, p. 1725)

[16] A purported “tetrachromacy test” has circulated on the internet since 2015. It uses an arrangement of bars in the colours of the spectrum, and asks viewers to report how many separate bars they can discern. Tetrachromats, supposedly, can make out more of the individual bars on this figure than can trichromats. Sadly, the test is a fake. Recall that computer monitors are designed to exploit trichromat vision, using three wavelengths of light to which trichromats are sensitive. So, they cannot produce colours that only a tetrachromat can see. The test is ably debunked at snopes.com/fact-check/people-4th-retinal-cone/. The tests used by Jordan and colleagues (2010) did not use computer displays, but light sources that produce a wider range of wavelengths.

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2 Tetrachromat colour

What then is cDa29's colour experience like? I take it that her acuity of vision must be reflected in some way in her experience of colour.[17] As I said in the Introduction, I consider two ways this could happen:

(i) She experiences hues of the kinds that trichromat viewers are familiar with, but discerns more fine-grained distinctions between them. For example, she may experience more subtle gradations of orange than we do in the corresponding area of the spectrum. Hues that are indiscriminable to trichromat viewers could, if they are produced by surfaces with different spectral reflectances, seem subtly different to her.

(ii) She experiences novel colours: hues that trichromats never do. Much as red and green appear to trichromats to be laid over blue and yellow in the visible spectrum – producing colours such as orange and purple – so cDa29 will experience further, novel colours laid over some or all of the colours most of us ordinarily see. So, just as the ability to see reds and greens corresponds to an ability to discriminate spectral reflectances unavailable to those with only blue–yellow colour vision, the ability to experience novel colours would correspond to the ability to make further fine grain distinctions within the visible spectrum.

These are not the only options – for instance, it could be that *all* the colours cDa29 experiences are novel – but it seems to me these two are the most plausible, and they will be my focus here.[18] How should we weigh them up? Jordan and colleagues (2010) do not address this question. But Jordan's view is related in the popular scientific journal, *Discovery*: "Unfortunately, she [cDa29] cannot describe how her colour vision compares with ours, any more than we can describe to a dichromat person what red looks like." (Greenwood, 2012) Jordan herself comments: "This private perception is what everybody is curious about, ... I would love to see that." (Greenwood, 2012) Although this is not the only way to read these remarks, the implication is that Jordan believes that cDa29 experiences novel colours. The alternative, that cDa29 experiences finer gradations of ordinary trichromatic experience, would be readily describable, and not worthy of such curiosity. Hardin is more sceptical. In his book *Color for Philosophers*, perhaps aware

[17] It is possible that the unusual visual distinctions tetrachromats are capable of involve an experience that is *not* an experience of colour. Macpherson discusses this proposal but does not support it. (Macpherson, 2020, p. 186) Another possibility is that these distinctions do not correspond to anything at all in the tetrachromat's experience – that is to say, their ability to make these distinctions is a form of blindsight. Empirical considerations allow us to quickly dismiss both ideas. cDa29 was asked about some features of her experience – for instance, she reported her experience of colour as smooth and not "patchy", suggesting both conscious access and colour experience (as opposed to some other visual experience). (Jordan et al., 2010, p. 6) Both blindsight and some non-colour visual experience would have been striking and notable effects to the subject and experimenters.

[18] I discuss the possibility that all the colours that cDa29 experiences are novel at the end of this section. Needless to say, it is a more radical proposal than the comparatively minimal claim that cDa29 sees *some* novel colours.

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of Jordan's developing work, he had mused on the topic of human tetrachromacy and the possibility of perception of novel colours:

> [C]onsider a hypothetical visual superwoman with an extra cone type and *three* chromatic opponent systems, two just like ours and a third, call it the "c-d" opponent system, involving cross-connections between the regular three cone types and the new cone type. She understands our color vocabulary very readily and can use it as well as we, but she pities our visual degeneracy, for she is a *tetrachromat.* (Hardin, 1993, p. 146)

But, writing in 2014, Hardin seemed underwhelmed by cDa29's feats of visual discernment:

> Is cDa29 the tetrachromatic visual superwoman imagined in *Color for Philosophers* as the bearer of three [chromatic] opponent channels and novel hues? Probably not, although the tests she underwent were designed to be strictly hard-nosed forced-choice stuff so as to admit of quantitative comparison and analysis. Nobody asked the woman about the *quality* of her experience. Perhaps cDa29 could be persuaded to give a little interview to philosophers in exchange for a nicer name like "Mary." (Hardin, 2014, p. 386)

So far as I am aware, cDa29 has declined to be interviewed, and remains anonymous.[19] Still, I think Hardin is unduly pessimistic. There is reason to believe that cDa29 does in fact experience novel colours – indeed, I think it will be hard to deny this conclusion. Let me start by picking up Jordan's suggestion that tetrachromacy is to trichromacy as trichromacy is to dichromacy – this, in some ways, will prove a useful way of thinking.

The dichromat has two operative cone types, which feed into one chromatic opponent channel. Note that many colour-blind people are only colour deficient, lacking full functionality in all three cone types.[20] Dichromacy – the complete absence of functionality in one of the ordinary cone types – is usually held to restrict the subject's experience to two elementary chromatic colours. For a red–green colour-blind dichromat – i.e., a person lacking L cones – these are blue and

[19] We know, however, that she is "a doctor living in northern England". (Greenwood, 2012) Apparently, the exchange Hardin proposed has not proved especially enticing.

[20] Broaches (2010) makes this point and shows that many red–green colour-blind people do in fact vividly experience red and green when they carefully attend to stimuli in context and over time. Colour deficiency also explains how glasses that "cure" colour-blindness can be effective for some people. They work only for kinds of red–green colour-blindness where function is retained in all three cone types, but the function of the M and L cones is compromised because their sensitivities overlap too much. The lenses block the wavelengths that create this problem, allowing the visual system to disambiguate signals from the cones and more fully resolve reds and green. (https://enchroma.com/pages/how-enchroma-glasses-work).

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yellow. (This is the most widely held account of dichromat experience, but it is a complex topic in its own right, and I footnote details about other approaches to understanding colour-blind experience.[21])

The trichromat's three cones feed into two chromatic opponent channels, and these are usually held to correspond to four elementary chromatic colours: blue and yellow, which are encoded in one channel, and red and green, encoded in the other. It is usually said that all the hues normally-sighted people see are combinations of these (orange being a yellow-red colour, and purple and red-blue colour).[22]

[21] Byrne and Hilbert (2010) call the kind of description of dichromat experience that I give the *reduction* view since it holds that dichromats experience a *reduced* range of the colours experienced by trichromats. It is supported by Viénot and colleagues (1995) and Hardin (1993, pp. 145–146). Byrne and Hilbert (2010) support a version of the reduction view, holding that red–green dichromats see only "yellowish" and "bluish" hues, rather than yellow and blue. (pp. 280–281) They understand "yellowish" and "bluish" to be determinables – so, yellowish is the determinable common to all the colours in the spectrum from yellowish greens through to oranges, which are its determinates. Byrne and Hilbert thus understand "yellowish" and "bluish", as they appear in dichromat experience, to be determinables without determinates, something, they claim, trichromats never see. On this basis they call these dichromat hues "alieni*sh*". (Byrne & Hilbert, 2010, p. 280) I do not take this view; rather I understand yellowish and bluish to be properties existing in a conjunct–conjunction relation with other colour properties. So, bluish can be experienced, in various degrees of saturation, in conjunction with other hues (in turquoise, for instance, bluish appears in conjunction with greenish). Equally, bluish can be experienced, by trichromats, as independent of other hues. The latter occurs when we see whitish blue or greyish blue, and equally when we see a transparent blue material, such as blue stained glass. So, as the ordinary reduction view holds, I take it that dichromats simply see a subset of those colours familiar to trichromats.

An exception to the reduction view holds that dichromats experience "alien" colours – novel colours in my terminology. The "alien" view of dichromat experience is discussed by Macpherson (2020, pp. 183–186), and examined by Byrne and Hilbert (2010, pp. 374–378) who put forward convincing reasons to reject it. P. M. S. Hacker, who presents one version of this view, claims that red–green dichromats see the surfaces that they have trouble distinguishing in terms of colour (those that trichromats see as red, green and grey) as a single, novel hue which he dubs "gred". Thus, dichromats see "[r]ubies, emeralds, and clouds" as "gred". Hacker (1987, p. 152) and Byrne and Hilbert (2010) point out the error in Hacker's thinking: "He has mistakenly taken the fact that dichromats confuse some reds, greens, and grays to indicate that dichromats see all red, green, and gray objects as having the same hue." (Byrne & Hilbert, 2010, p. 286, n. 26)

Another exception to the reduction view, developed by Broackes (2010), shows that there are ways that the visual systems of a true dichromat could exploit the information encoded in a single opponent channel to accurately infer the presence of other elementary hues in the environment, beyond the two encoded in the usual way in the opponent channel. (pp. 335–337) At present however, it is unclear whether the dichromat visual system in fact does this, and if so, whether these inferences are associated with experiences of other elementary hues.

[22] I take it that trichromat vision accords with the phenomenology attributed to it by Hering (1964). That is to say, even though the activity of the opponent channels does not precisely correspond to colour experience (as we saw above), it does determine the elements of trichromat colour experience. Each of the chromatic opponent channels allows the processing of a pair of elementary hues – i.e., red and green, and blue and yellow. All other chromatic colours, phenomenologically speaking, are combinations of these. (Hering, 1964, p. 42) This remains widely accepted today: "All [chromatic] colours can be described in terms of four non-reducible 'unique' hues: red, green, yellow, and blue." (Stoughton & Conway, 2008) "Hue can be described by four separate sensa-

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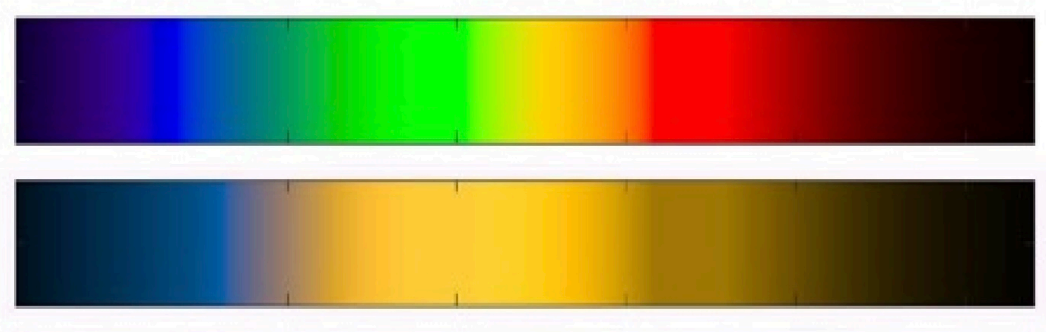

Figure 1: Top: spectrum as it appears to a normal trichromat observer. Bottom: spectrum as it appears to a dichromat viewer with protanopia (i.e., lacking functional L cones). From (Li et al., 2020, p. 172)

In fig. 1, the upper band shows the spectrum of visible wavelengths of light as a trichromat sees it. The lower band shows how a dichromat subject lacking L cones sees it. We can understand the trichromat viewer's experience of the spectrum as differing from the dichromat viewer's experience it by simply having red and green bands laid over it, producing bands of red and green, as well as orange and purple. (again, this relies on understanding orange as the phenomenal mixture of red and yellow, and purple as the phenomenal mixture of red and blue). The dichromat viewer still sees most of the spectrum as being coloured, but not with all the colours that the ordinary viewer sees, and accordingly, they are not able to make as many colour distinctions as can an ordinary viewer. This inability manifests in two ways. First, some wavelengths that the normal viewer sees as different in hue will appear the same hue to the dichromat. That is, the dichromat will have more metamers than the trichromat. Second, the normal viewer has phenomenal access to a larger number of colour categories, and can use these to quickly group and distinguish and coloured objects. This allows them, for example to quickly sort collections of coloured objects into broad colour categories, such as red, orange, yellow and green. The dichromat, if they are able to differentiate at all between corresponding wavelengths of light, can only do so by carefully assessing subtle differences in their spectrum. (From here on, I will speak of the different kinds of chromat viewers as having their own spectra – the dichromat spectrum, the normal or trichromat spectrum, and the tetrachromat spectrum. These refer to their experiences of the objective, physical spectrum, comprised of refracted light.)

We can extend this way of thinking to predict what tetrachromat experience could be like. A fourth kind of cone, if it is to be of use to the visual system, needs

tions of red (R), green (G), yellow (Y), and blue (B)." (Abramov & Gordon, 2005, p. 2143) "There exist four colours, the *Urfarben* of Hering, that appear phenomenologically unmixed." (Mollon & Jordan, 1997, p. 381). I have to admit some personal discomfort with this view. Does orange really appear no more than a yellowish and reddish colour? Does purple really look merely reddish and bluish? But I put aside these concerns for another time.

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to feed into at least one new opponent channel.[23] Since the opponent channels each code two colours, one extra channel would presumably code two further elementary colours. So, the tetrachromat spectrum might feature further bands of colour, beyond those the normal viewer sees, which appear laid over the normal viewer's spectrum, much as the trichromat's colours appear laid over the dichromat's spectrum. Just as this gives the trichromat extra powers of visual discrimination in comparison to the dichromat, so the tetrachromat will have powers of visual discrimination unavailable to trichromats. Accordingly, we can expect these powers to manifest themselves in two ways. First, the tetrachromat will be able distinguish between fine-grained differences of colours, which to normal viewers are metamers. Second, the tetrachromat may be able to use the larger range of colour categories phenomenally available to them to quickly distinguish between kinds of coloured objects, or recognise them as similar.

As Hardin says, Jordan and colleagues (2010) did not ask cDa29 about the quality of her experience, which could have included, for instance, how the spectrum appeared to her. Or at least, they do not record doing so. But I will argue now that their study does in fact give us enough evidence to conclude that cDa29 experiences the spectrum as containing a band of novel colour. Jordan and colleagues' (2010) first experiment makes use of changing proportions of red and green light. These are adjusted by the subjects using an analogue control system. The differing proportions of red and green in the stimuli can be mapped along a linear continuum, from 100% red and 0% green through to a midpoint of 50% red and 50% green, to 0% red and 100% green. This continuum of stimuli can be thought of as producing corresponding sensations that can also be arranged in a linear continuum, from red at one end, gradating smoothly through orange and yellow, through to green at the other end. The continuum of sensations is smoothly gradated, without gaps of any kind.[24] Now, Jordan and colleagues (2010) show that cDa29 is unable to match the sensation produced by certain orange wavelengths to the sensations produced by *any* combination of red and green wavelengths. Since the continuum of combinations of red and green stimuli produces a full continuum of orange sen-

[23] A new opponent channel could come from the combination of any of the tetrachromat's cone types. That is also to say that the tetrachromat could, at least in principle, have a number of new opponent channels beyond those of trichromats. Trichromats have three channels: L v M, S v (L+M), and (L+M) v -(L+M). Adding a fourth cone could allow for the development of one new channel, say L′ v M. Equally, though, it could produce three new channels, e.g., L′ v M, S v (L′+M), (L′+M) v -(L′+M). For simplicity, I will assume the minimal claim, that tetrachromats possess just a single extra channel. I am grateful to an anonymous referee for drawing my attention to the possibility of these multiple extra channels.

[24] Although it does not bear on my argument, the precise correspondence of the continuum of stimuli to the continuum of sensations is complex in practice. The continuum of stimuli will include points (lying close together) that are physically distinct, but are visually indiscriminable – that is, they are metamers. Depending on how the continuum of sensations is constructed, these may correspond to points, lying close together, that are qualitatively identical to one another. This does not change the claim on which my argument depends, that the continuum of stimuli produces sensations that can also be arranged in a linear continuum.

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sations from red through to yellow, the colour sensation that cDa29 has cannot lie anywhere on this continuum of oranges – there is no space for it there, no gaps to fill.

Where, then, can the tetrachromat's sensation prompted by the orange wavelength fit in? We can develop an answer by imagining a similar problem from the dichromat's perspective. They might equally wonder where the reds and greens seen by normal viewers could fit into their colour experience. The spectra shown in fig. 1 give us the answer: reds and greens simply appear overlaid on the dichromat spectrum. Where they overlap with a colourless part of the dichromat spectrum, shown as grey in fig. 1, they appear in their pure form, as pure red and pure green, untinted by other colours. Where green overlaps with blue and yellow, we find bands of blue-green and yellow-green respectively, and where red overlaps with blue and yellow, we find violet and orange.[25]

So, we can find a solution to the lack of gaps for tetrachromat colours to occupy by instead understanding tetrachromat colour as appearing similarly overlaid on the trichromat spectrum. This means that the tetrachromat's novel colours will appear combined with the trichromat colours, much as, say, green and blue appear to overlap or intermix in the trichromat spectrum. It could also be that there is a point in the spectrum where the normal operation of trichromatic colour processing is inhibited, allowing the tetrachromat's novel colour to be seen in its pure from, as there are points where, for the trichromat, red and green are seen in their pure form. While this perception of pure novel colours is possible on my account, it is not necessary – it might be that novel colours are only perceived as tinted with other colours.

I have examined two ways in which cDa29's perception of monochromatic orange light could fit into the spectrum she perceives – either it fits into gaps between familiar trichromat colours, or it is experienced as overlaying these trichromat colours. We have seen that the first possibility is not viable – there are no gaps in the spectrum that trichromats perceive, so instead, I take it that the tetrachromat colours appear to overlay the familiar trichromat colours. It will also be apparent that these overlaid colours cannot be the finer gradations of familiar trichromat colours – rather, they must be novel colours. Why? All the possible shades between red and yellow can be located within the trichromat spectrum, even though trichromats cannot discriminate all of these. To be discernible from all these colours, the tetrachromat must experience them as a colour qualitatively unlike any of those colours. That is to say, they must be a novel colour.

I said above that we can expect the ability to see novel colour to manifest itself in two ways. We have seen this ability manifest in the first way: cDa29 is capable of making fine-grain distinctions between wavelengths that trichromats cannot discern. There is also evidence that cDa29 manifests this ability in the second way. Jordan and colleagues (2010) report that she not only completed their tests correctly, but also quickly and easily. Presumably, then, she is noticing at least some

[25] Violet occurs at the other end of the spectrum from red, where the L cone is also active.

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of these differences not in virtue of subtle differences – since these involve longer, careful regard, but in virtue of differences between colours that appear obtrusive to her. That too suggests that she makes use of a colour category unavailable to normal viewers to quickly distinguish between kinds of coloured objects. The work by Jordan and colleagues (2010) therefore implies that cDa29 sees a novel colour, distinct from orange, yellow, and red, but lying in the area of the spectrum that trichromats recognise as orange.

One may wonder, is it right to put such stock in Jordan and colleagues (2010)? After all, the crucial data in their study derives from a single individual. There are good reasons to think so. As I have mentioned, Jordan, says "there is no doubt that she [cDa29] is the real deal". (Higgins, 2022) The results of the study are the product of a long search. Jordan, who works at Newcastle University, began working with Mollon in his laboratory at the University of Cambridge, and has spent twenty years looking for a tetrachromat who can clearly and incontrovertibly make use of their extra cone. Jordan and Mollon (1993) marks an early stage in this research.) Jordan is aware of the doubts that her work raises, and the scope for fraudulent "tetrachromats" to mislead researchers. Jordan says of one such subject, "[s]he was so clever … She had heard the shutters releasing the beams of light and worked out that one click was for yellow, two clicks for the red–green mixture." Following that, Jordan put headphones streaming white noise on her subjects. (Higgins, 2022) Although his interpretation of Jordan's work is different from mine, we have seen that Hardin has no reservations about their methods: "the tests she [cDa29] underwent were designed to be strictly hard-nosed forced-choice stuff so as to admit of quantitative comparison and analysis." (Hardin, 2014, p. 386) The tests, as described by Jordan and colleagues (2010), are indeed impossible for trichromats to pass. Moreover, cDa29 was tested multiple times in each experiment, and the tests were repeated two months later. (Jordan et al., 2010)

Should it be concerning that no other tetrachromats with cDa29's abilities have yet been found? Certainly, it would be encouraging if we were aware of more such tetrachromats. But it is not especially surprising that they have not been found. There are several considerations here. First, these capacities are expected to be rare: only a small fraction of people have the right genetics, expressed in the right way, to support tetrachromacy. Jordan & Mollon estimate that of the UK population at the time of the 2012 census (63.2 million) "only 48,585" will have a fourth cone optimally separated in its wavelength sensitivity from the ordinary cones, and of these, only a small proportion of are expected to develop the abilities that cDa29 displays. (Jordan & Mollon, 2019, p. 133) Second, only two groups have been searching for tetrachromats – those led by Jordan and Jameson – and these groups have the capacity and funding for only relatively small studies. Third, tests must be conducted in person and with specialised equipment. (Jordan & Mollon,

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2019, p. 133) Fourth, it may be that recruitment strategies for experimental subjects have been suboptimal. (Jordan & Mollon, 2019, p. 133)[26]

Lastly, and importantly, I have said that Jordan's group's methods are exceptionally careful and strong. Indeed, a case may be made that they are in a sense *too* stringent. In Section 4 we shall see that some other subjects studied in (Jordan & Mollon, 1993) show clear indications of functional tetrachromacy, even though they did not convincingly pass Jordan & Mollon's tests. That is to say, it seems that their methods exclude some functional tetrachromats who do not have the full range of function shown by cDa29.

So, what can we say so far about what it is it like to be a tetrachromat? If someone were to ask what it is like to be a trichromat, one way of answering it would be to say that it involves seeing all the hues that trichromats see in the spectrum.[27] A functional tetrachromat such as cDa29 could describe seeing extra hues in the spectrum. In particular, it seems that cDa29 sees one extra hue, a novel colour, within the area where normal viewers see only orange. Looking at a rainbow, cDa29 would be able to pick out a further distinct band of colour invisible to most of us. Perhaps cDa29 would see more such bands of tetrachromat colour in the rainbow. One possibility is that tetrachromats experience not one but two novel colours. Dichromats, with one chromatic opponent channel, are usually taken to perceive two elementary hues; trichromats, with two such channels, are usually taken to perceive four. So it might be that tetrachromats, assuming a minimal physiological change in their opponent processing, have a further such channel, can be expected to experience two further elementary hues – that is to say, novel colours. Tetrachromats, then, would see two extra coloured bands within the rainbow, corresponding to these two novel colours. They might identify more bands of colour too – much as trichromats identify more bands of colour in the spectrum than those corresponding to four elementary colours – they also tend to identify orange, violet and sometimes indigo, so the tetrachromat might also identify separate bands corresponding to areas where novel mixtures meet familiar trichromat colours. Suggestively, one of the individuals investigated in (Jordan & Mollon, 1993), called "Mrs M" in popular science and news reports, says she sees rainbows as having *ten* bands of colour.[28] Another possibility to consider is that some tetrachromats may develop more than one new opponent channel,

[26] Jordan and colleagues (2010) recruited women with sons who were colour-deficient anomalous trichromats, where Jordan & Mollon now think that they would have done better recruiting minimally anomalous trichromats. (Jordan & Mollon, 2019, pp. 131–32133)

[27] There is an exception: purple (understood as a redder colour than violet) is a non-spectral hue, since it does not correspond to any single wavelength of light. (Hardin, 1993, pp. 41–42) Instead, it is produced by the stimulation of S and L cones together, that is to say, through stimulation by both high and low wavelengths of visible light.

[28] This does not appear in (Jordan & Mollon, 1993), but is recorded in a newspaper article (Ings, 2007). More details appear in (Zorpette, 2000).

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which would presumably allow a wider range of colours again to be discerned in the rainbow.[29]

Figure 2: Evelyn De Morgan, *S.O.S.*, 1914–16, oil on canvas, 93.4×65.5cm.

These thoughts raise another possibility, that a tetrachromat painter could depict the extra bands of colour they see in a rainbow. To trichromats, unable to see tetrachromat colours, such an image might simply look like an ordinary picture

[29] On the possibility of tetrachromats having more than one extra channel, see n. 23. Note, if it were the case that *all* the colours a tetrachromat saw were novel colours (see below in this section), that would change the way they saw a rainbow accordingly, but it would, presumably, not further alter the number of bands the tetrachromat saw in the rainbow.

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of a rainbow. But it might stand out through the unusual banding that the artist could give it. On this basis, we can speculate that the painter Evelyn De Morgan (1855–1919) was a tetrachromat. Several of her paintings show rainbow mandorlas and auras, which she often gave unusually complex and subtle banding (see, for an example, fig. 2).

Also, there is a possibility that *all* the colours the tetrachromat sees are novel. That would seem to follow, for instance, if one takes a structuralist view about the phenomenal quality of colours, i.e., that "the whole structure of quality space affects the phenomenal character of each individual experience". (Fleming & Shea, 2024, p. 904) Equally, it could also follow if colour quality depends on physiological or functional features of the visual system, and the new opponent pathways affect the physiology or function of existing channels in some way. I will not linger on these possibilities, as my focus is on establishing the comparatively minimal claim that tetrachromats see at least one novel colour. If there proves to be appetite for the idea that *all* the colours tetrachromats see are novel, its proponents should find my arguments a useful beachhead.

In any case, such novel colours will resist description, except to say that, for those who see them, they will be readily discriminable from other colours (since cDa29 was quickly and reliably able to make such discriminations), and that they may appear as mixtures with certain other colours and not with others – that is to say, they may exhibit opponency.[30] This is no more than a trichromat could tell a red–green colour-blind dichromat about red and green: that they form obtrusive bands in the spectrum distinct from other hues, and that they can appear mixed with some colours, but not with others (i.e., red and green, being opponent colours, do not, at least ordinarily, appear in phenomenal mixtures with each other). All that is only to agree with Jordan's view about cDa29, expressed to *Discovery*, that "[u]nfortunately, she cannot describe how her colour vision compares with ours, any more than we can describe to a dichromat person what red looks like." (Greenwood, 2012)

3 "Forty shades in a single blade of grass"

Kimberly A. Jameson's research group has developed a different approach to studying tetrachromacy. Unlike Jordan's group, Jameson and her collaborators compare a tetrachromat's abilities of visual discrimination in more complex visual environments, akin to those in which people normally exercise their powers of visual discrimination. (Jameson et al., 2015, pp. 23–24) Jameson's group has given particular attention to an individual, the painter Concetta Antico, who they conservatively describe as a "potential tetrachromat" (Jameson et al., 2015, pp. 23–24), although a more recent work includes research on other tetrachromats (Jameson et al., 2020).

[30] Up to here, my account of tetrachromat experience parallels that conducted in rather more hypothetical form by Thompson (1992) But Thompson thinks it possible that an understanding of physical facts could give us knowledge of the qualitative character of novel colours.

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In a passage much quoted in the popular media, Jameson and Winkler (2014) say, "we believe Concetta Antico represents a 'perfect storm' for the realization of tetrachromatic color vision." (p. 3) That is, she has the right genetics (Jameson & Winkler give a technical account of the tests undertaken) and her history as a painter gives her the right environment in which to realise her capacity for tetrachromacy. Jameson and colleagues (2015) compared Antico to three control participants: a non-artist trichromat, a trichromat painter, and another "potential" tetrachromat, who like Antico has the genetic characteristics for tetrachromacy, but is not an artist. None performed as well in the experiments as Antico. They found that she was "more sensitive to subtle differences in a range of colors compared to control participants", that she "exhibits enriched color experience in dim light conditions (low daylight, or low photopic, vision) such as in shadows and for low ambient levels", and that she is most responsive to the "conditions involving 'reddish' stimuli." (Jameson et al., 2015) They describe all these unusual abilities as consistent with the presence of a fourth cone sensitive to long wavelengths. (Jameson et al., 2015)

Drawing on Jordan's endorsement, Antico has become the world's best-known tetrachromat, interviewed by *The Guardian*, *Vogue*, BBC, and Munsell Color Blog, among other outlets. (Adcock, 2022; Blog, 2015; Robson, 2014; Seaberg, 2014) Antico mostly paints landscapes in a colourful Impressionist style. Antico insists that her paintings are true to her experience: "It's not just an affectation and it's not artistic licence … I'm actually painting exactly what I see. If it's a pink flower and then all of a sudden you see a bit of lilac or blue, I actually saw that." (Adcock, 2022) She also says that she sees fine-grained distinctions that ordinary viewers are oblivious to: "When I look, I see hundreds of grays." (Blog, 2015) "Where you see grays, I see a rich and beautiful mosaic of lilacs, lavenders, violets, emeralds." (Higgins, 2022) "Looking at a red rose, I see shades of red, bits of green, lilac, yellow, orange and more. For me, everything is broken into shades. I'm looking at a violet wall right now, but it's not violet, it's gold and grey with little bits of green. There are soft subtle transitions of color in everything, it's like a mosaic." (Blog, 2015) These descriptions are consistent with the appearance of many of her paintings, which show the local colours of her subject matter streaked with other hues.

Antico's remarks, coupled with the appearance of her paintings, suggest that they communicate something of her experience to normal viewers. But Jordan and Mollon (2019) sound a note of caution: "Will a potential tetrachromat be a more successful artist? If she uses her colour palette veridically to render her sensations, then it is not clear how she can communicate the added richness of her private gamut to those who live in an impoverished perceptual world." (p. 133) Say that Antico reproduces in her paintings features that trichromats are unable to perceive in their visual environment. Trichromats will no more be able to discern those same features in her paintings. By this way of thinking, Antico's paintings, if genuinely faithful to her visual experiences, should appear to trichromat viewers as entirely ordinary and unremarkable pieces of realism. This applies equally whether Antico sees novel colours or subtle gradations of colours familiar to trichromats. How

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then should we account for the unusual colours in Antico's paintings, which she says are faithful registrations of her perceptions?

Assuming that Antico is honest, I see two possible responses to this question. The first is to point out that her paintings do indeed appear ordinary and unremarkable within one established tradition of painting, that of the Impressionists. The unexpected colours in Antico's work are comparable to those seen in the 1880s Impressionism of Monet, and the Neo-Impressionism of Pissarro and Seurat, where contrast effects are painted in, so that shadows are painted blue or indigo (Reutersvärd, 1950), and local colours are interpenetrated with their complementary hues (Roque, 1996).[31] The second way to account for the unusual colouring of Antico's painting is to understand Antico as translating colour differences imperceptible to us (trichromats) into colour differences that we can perceive. Jameson and colleagues (2015, p. 35) take this approach, suggesting that, aware of our visual shortcomings, Antico is exaggerating these effects to make them apparent to trichromat observers. This approach is attractive in the case of Antico's paintings of subjects in low light conditions. *A Tetrachromat Moon*, 2014, (fig. 3.) is her most striking work in this context. This depicts a full moon surrounded by a richly coloured halo of light. Such haloes can appear when the full, or near full moon is seen through clouds – a common but rarely noticed phenomenon. Making allowances for her impressionistic style, the painting captures the faint colours of this effect with remarkable accuracy. The outer ring of the halo is an orangey brown, and within it, the moon is surrounded by a pale blue. I am not aware of any other painting that shows such a halo around the moon with this accuracy. The closest example I know is by the Norwegian painter, Johan Christian Dahl, whose *Study of Clouds at Full Moon*, 1822, shows the brownish halo, but not the bluish colour within it that Antico captures. In life, I find the pale blue colour is especially difficult to notice, but apparent when comparing the colour to that of the sky seen through the clouds outside the halo's brown ring. Although hard to detect in life, such details of colour can show clearly in photographs, and so a warning should be added – it is possible that Antico relied not on her own perception, but on such a photographic source. Of course, it should also be said that unless her ability to work in low light is truly superhuman (and recall Jameson et al., 2015) only describe her colour vision as functional in "dim light conditions"), she cannot have painted this scene from life. Like other painters of nocturnes, she will have relied on memory, notes, photographs, or some combination of these.[32]

[31] One may also wonder whether contrast effects should be painted in, as seen in Impressionism and Neo-Impressionism. After all, if a painter carefully reproduces on canvas the configurations of colour in their subjects present, those configurations of colour should produce the same contrast effects in painted form as they do in life. For a sophisticated response to this question, arguing that painters are justified in depicting contrast effects, see (Roque, 1996).

[32] Whistler, to take the most prominent example, committed night scenes to memory and painted them in the studio. (Dorment & MacDonald, 1994, p. 120)

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Figure 3: Concetta Antico, *A Tetrachromat Moon*, 2014, oil on canvas, 76.2×91.4cm.

Let me turn now to the question of whether Antico sees novel colours or merely fine gradations of familiar hues. The descriptions Antico gives of her experience of colour, quoted above, are striking in that they do not suggest that she sees novel colours. Although she sees colours in places where normal viewers may not expect to see them, she always describes the colours she sees using our familiar language of colour terms, and seems content to do so. Others who identify as tetrachromats seem to have comparable experiences. One is Maureen Seaberg, a writer and photographer who, like Antico, has the genetic basis for tetrachromacy. (Seaberg, 2014, p. 232)[33] She describes a trip to an Irish bed-and-breakfast. The owners, she recounts,

> called me to a window to look out at the fields. I had arrived late the night before and hadn't yet seen the countryside in all its verdant glory. "Do you see them, the forty shades of green?" my host asked. For most people, the old Irish cliché is hyperbole, but to me it was a gross understatement – I could see forty shades in a single blade of

[33] Seaberg's test was administered by Jay Neitz. (Seaberg, 2014, p. 232) Seaberg is another "celebrity" tetrachromat, and has designed a line of lipstick colours for MAC Cosmetics. (Hou, 2016)

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> grass. "There are so many more than that," I said, smiling at the sight of emerald, yes, but also peridot and jade and malachite and sea glass and verdigris and everything in between. (Seaberg, 2014, p. 232)

Seaberg, who has researched other tetrachromats, also mentions Megan Arquette, an interior designer from Los Angeles, "[who] recalls waxing lyrical over the color of the sidewalk after a rainstorm. 'For me, these everyday things are absolutely alive with depth and hue' she said". (Seaberg, 2014) Though specific colours are not mentioned, there is no suggestion that they see colours unfamiliar to trichromats, although they may experience these in unusual ways, perhaps allowing them to make the fine-grain distinctions documented by (Jordan et al., 2010). That is to say, nothing suggests the experience of novel colours. This is further supported by Antico's belief that the colours she sees are colours that normally-sighted individuals can also come to see, if they learn to attend carefully. Describing her practice teaching painting to students, she says: "I'd do a lot … of, 'OK, let's look at this together. Can you see that?' And if they'd say no, I'd be like, 'Well, let's look a little closer' … When they see it, they will paint it, so my students' paintings became much richer."[34] (Adcock, 2022)

Altogether, there is enough overlap in these accounts to suggest a picture of tetrachromat experience that, unlike cDa29's experience, does not involve novel colours. Instead, it seems to involve perceiving more fine-grained visual distinctions between trichromat colours than those usually available to normal viewers. One can detect a difference between how these fine-grained distinctions appear in the accounts of Antico – where they are seen in a variety of apparently iridescent colours – and Seaberg – where the fine-grained distinctions between greens appear, more mundanely and simply, as different shades of green. But these differences are fully articulated in the language of ordinary colours – neither appears to describe novel colours as part of their experience.[35]

4 "The wrong kind of orange"

How can we reconcile these different accounts of tetrachromat experience – cDa29's experience of novel colours, with Antico's and Seaberg's subtle and complex experience of ordinary trichromat colours? Could there be different kinds of tetrachromats, their neurology adapted in different ways to make use of a

[34] The idea that visual perception can be enriched through the practice of drawing and painting is reputable in art education, and core to some ways of thinking about art (e.g., Albers, 1975; Ruskin, 1864).

[35] What is to account for the differences in Antico's and Seaberg's descriptions? While I will have more to say about their experience of colour in the next section, I will focus on different issues there. A simple approach would be to see them as describing tints of the same colour in different ways, Antico giving more weight to the tinting colour, and Seaberg giving more weight to the tinted colour. In the absence of further evidence, that is the approach I am inclined to take.

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fourth cone type? Or is there, broadly speaking, only a single kind of tetrachromat, which we have been given different views of so far?

I think the second conclusion is more likely the correct one. A key to understanding how the different accounts can be reconciled can be found in (Jordan & Mollon, 1993). This marks an early point in their project to find functional tetrachromats. It is easily overlooked in the literature, as they present their study as inconclusive, since their subjects did not fully satisfy the researchers' demanding standards of proof of functional tetrachromacy. However, it is clear in retrospect that the feats of visual acuity that they record there align well with those of cDa29.

Like Jordan and colleagues (2010), Jordan and Mollon (1993) discovered subjects who were unable to match a red–green mixture to an orange light. They observe that such "match refusals … provide preliminary evidence for tetrachromacy. This would be of the strong form." (Jordan & Mollon, 1993) "Strong", here, indicates that the tetrachromat has the apparatus needed to make use of the extra information that a fourth cone provides – Jordan and Mollon (1993) take this to be an extra opponent processing channel, into which the fourth cone feeds. (p. 1505) Why do they take this result to provide no more than preliminary evidence? Unlike Jordan and colleagues (2010), the earlier study did not include tests requiring discrimination between stimuli that are indiscernible to trichromats. That test is more decisive, since, provided it is well-designed, subjects cannot simulate reliable discrimination. By contrast, it is possible that subjects could misreport their ability to fail to match stimuli that are physically different.

Of particular interest to me, Jordan and Mollon (1993) asked the participants about their experiences, and report their responses. Subjects who "could not find a red–green mixture that satisfactorily matched the monochromatic yellow" were asked to describe the difference in hue that they experienced. (Jordan & Mollon, 1993) They record these replies: "I want to be able to add more orange to the mixture, not red." "It is simply the wrong kind of orange." "It is the wrong kind of orange; it needs more yellow, it looks rather pink when I add more red." "If the joystick [used to adjust the red–green mixture] is just slightly off to the left-hand side, the mixture looks too green, but pushing it slightly more to the right makes it look pink and not orange." (Jordan & Mollon, 1993)

If we hold an orthodox understanding of orange as a yellowish reddish colour (Hering, 1964, pp. 42–43), these comments seem to indicate a misunderstanding of the concept. The subject who says "I want to be able to add more orange to the mixture, not red" seems to have misunderstood that one makes yellow more orange *by* making it appear more red. The subjects who say that it "is the wrong kind of orange" seem to misunderstand that all oranges, grading from yellow through to red, are available for them to select in the experiment. The participant who complains that the mix needs "more yellow" seems not to understand that this can be readily added by pushing the joystick to increase the green component (which will increase the yellow effect for trichromats, before reaching green). The last participant says: "If the joystick is just slightly off to the left-hand side, the

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mixture looks too green, but pushing it slightly more to the right makes it look pink and not orange." This suggests that the subject does not even perceive orange and yellow in this sequence of colours running from green through to red.

Is it possible that each of these subjects – mature women – has misunderstood such basic concepts of colours? Here is another explanation, which I take to be more plausible: the subjects of these experiments apply ordinary colour terms to roughly the same parts of the spectrum that trichromats do, but they see different colours in those parts of the spectrum. That is to say, they use the terms "orange" and "yellow" to indicate the presence of a novel colour, whether in a pure form, or as tinting the colours trichromats recognise by these terms. How could this different reference have occurred? Most of those things in our visual environment that are exemplary instances of orange and yellow are not so through combining red and green light – orange and yellow fruit, orange and yellow paint, and the orange and yellow seen in rainbows are all so in virtue of reflecting or refracting light of orange and yellow wavelengths.[36] Both colours are around the wavelength to which the fourth cone of the tetrachromats researched by Jordan & Mollon is most responsive. So, it is reasonable to think that tetrachromats would identify the sensations associated with the peak response of this cone as orange or yellow, rather than the sensations that trichromats know as orange and yellow.[37]

More generally, this suggests that tetrachromats use just the same colour terms that trichromats do, and use them to refer to much the same objects that trichromats do. This use of "trichromat" terms is consistent with the fact that tetrachromats do not themselves tend to understand the greater complexity of their colour experience. As we have seen, Antico and Seaberg assume they see the same kinds of colours as trichromats, and Jordan says that cDa29 "had no idea" that her vision was unusual. (Higgins, 2022)

This approach also casts new light on the experiences of Antico and Seaberg. In the last section, the evidence suggested that they did not experience novel colours, but only finer distinctions between the colours familiar to trichromats. We can now see how that conclusion can – and I think should – be revised. For although these tetrachromats use familiar colour terms, we can now appreciate that, like Jordan's subjects, they probably use these terms in different ways to trichromats. I give four reasons for taking this position. First, novel colours explain the ability to make unusually fine visual distinctions. Just as the ability to discern red and green allows finer distinctions to be made than those available to subjects who see only blue and yellow hues, so the ability to discern novel colours within the visible spectrum may further refine visual acuity. Can this explain Seaberg's apparent ability to see a vast multitude of greens? To give a very rough calculation, if each

[36] For reflectances of paint see (Cosentino, 2014, p. 61); for reflectances of fruit, see (Burns, 2015, p. 3).

[37] It is unlikely that a novel colour will be associated with precisely the peak sensitivity of the fourth cone, since this is not the case for the peak sensitivities of the M and L cones, which are not precisely associated with green and red.

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of the many subtle greens normally seen by a trichromat can be inflected with ten discriminable shades of one novel colour, that will mean that the tetrachromat can discriminate an order of magnitude more shades of green than can the trichromat. So, the answer is yes: the ability to perceive a novel colour can indeed explain the abilities Seaberg describes.

Second, on the face of it, it would be a strange coincidence that Jordan's and Jameson's groups had come across substantially different kinds of tetrachromats, since they use the same genetic tests to screen their subjects. So, other things being equal, it is reasonable to think that they are studying the same phenomenon.

Third, perception of novel colours also explains something that Mrs M, Antico, and Seaberg all comment on: they often find themselves beset by clashing colours that they say go unnoticed by trichromats. "People will think things match", says Mrs M, "but I can see they don't." (Zorpette, 2000) Antico says, "you can't just put a pair of red shoes with a red dress. They don't match. A lot of times I see someone trying to color coordinate and it's completely off." (Blog, 2015) Seaberg has the same problem: "When clothes shopping … apparently matching tops and skirts seem to be a different shade … clashing horribly – even though no one else seems to notice it." (Robson, 2014) Seaberg also finds "[t]he grocery store … a nightmare… It's like a trash pile of colour coming in at every angle." (Robson, 2014) It is true that fine-grain differences in colours can also create unpleasant effects – two colours that do not quite match can appear awkward placed next to one another, but they don't "clash horribly". So, these accounts suggest that Mrs M, Antico, and Seaberg detect extra, highly saturated colours – novel colours – that trichromats do not see. Otherwise, what could be the source of these clashes?

Fourth, the only physiological account we have that explains the development of functional tetrachromacy involves the development of a new opponent processing channel (or channels). That explanation, as we have seen, supports a phenomenology featuring novel colours, since each of the familiar opponent processing channels corresponds with the perception of certain elementary colours: a pair of opponent hues on Hering's account. While a tetrachromat experience involving perception of finer distinctions among familiar colours seems phenomenologically simpler than one involving novel colours, there is no existing physiological model that supports it. We might wonder if this could be achieved by feeding the tetrachromat's cones into the normal trichromat apparatus of opponent processing. Jordan and Mollon (1993) call this model "weak" tetrachromacy. As they put it, there would be "four separate types of cone, but only three independent postreceptoral channels." (Jordan & Mollon, 1993, p. 1496) However, the weak tetrachromat "would accept trichromatic color matches", including the matches between mixtures of red and green light which trichromats find indiscernible from orange wavelengths. (Jordan & Mollon, 1993, p. 1496) That is to say, the weak tetrachromat would be no more capable of making colour distinctions than a trichromat

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viewer.[38] One way of thinking of this is to understand the tetrachromat's four kinds of cones as providing only a confused version of the normal trichromatic input, which the opponent processing channels are able, more or less, to make sense of in the ordinary way. So, weak tetrachromacy, should it exist, cannot produce a more fine-grained experience of familiar colours than can ordinary trichromacy.[39]

5 Conclusion

I have argued that tetrachromats see novel colours, and that this explains their unusual acuity of vision. The conclusion that there are novel colours may seem a radical and surprising one. Perhaps it might even provoke an incredulous stare. I will say something about the sources that underlie this kind of response, for if we are to be accepting of novel colours, we not only need arguments in their favour, which I have given; we also need a sense of how they could fit into our worldview. There seem to me two such sources of pre-theoretical incredulity at novel colours. First, they defy the common-sense understanding that surfaces really have just the colours that they usually appear to have. Second, they depart radically from our usual experience of colour: most of us have never seen novel colours, and never will. I address these concerns in turn.

The intuition that surfaces really have just the colours that they appear to have – when observed by physiologically and psychologically "normal" viewers under "normal" viewing conditions – has long been questioned by science, and is now widely rejected in philosophy also. A long-standing scientific tradition supported by Galilei (1960), Locke (1961), and given a contemporary articulation in (Seth, 2022), understands colours as either produced by or otherwise dependent on the activity of the visual system, rather than simply being properties of the surfaces in which they seem to inhere. This understanding has also found advocates among philosophers (e.g., subjectivists such as Hardin (1993), and relationists such as Cohen (2009) and Matthen (2005)). Even those philosophers who defend the intuition

[38] There would be some differences though: Jordan and Mollon (1993) add that the weak tetrachromat "would not exhibit the stability of matches under adaptation" typical of trichromacy. (p. 1496)

[39] It is also worth noting that Jordan and Mollon (1993) suggest that, despite a greater physiological complexity, strong rather than weak tetrachromacy may be the norm for those subjects with four kinds of cone cells:

> Midget bipolar cells and midget ganglion cells [parts of the opponent processing pathways]… commonly draw their centre input from a single long- or middle-wave cone. … [I]f a woman has three types of cone in the long-wave/middle-wave spectral region, she should have an additional type of midget ganglion cell. If the signals of these cells remain segregated throughout the parvocellular pathway [i.e., throughout opponent processing], then to explain tetrachromacy, we need only to suppose that the cortex can identify subsets of inputs that are correlated. It is commonly assumed that the cortex exhibits just such a property. (p. 1505)

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that surfaces have the colours they typically appear as having to normal viewers, now tend to make space for the possibility that surfaces also have colours that other kinds of viewers with differently constituted visual systems can detect (e.g., Allen, 2016). Among animals, such viewers include avian and piscine tetrachromats. Such animal examples pave the way for us to similarly understand human tetrachromats as experiencing novel hues that inhere in surfaces no less than those familiar to normal human viewers. Thus, from both scientific and philosophical perspectives, a broad consensus now resists the common-sense ideas that surfaces have just the colours they ordinarily appear to have to normal, human viewers.

Let me turn to the second source of incredulity, that novel colours are utterly foreign to most of us. The fact that most of us can neither see nor imagine them is apt to generate a scepticism that rational argument alone struggles to dispel. This scepticism is deeply ingrained. Consider the naturally dichromat squirrel monkeys, Dalton and Sam, transformed into trichromats. We don't know just what their new-found colour experiences are like. And yet, we find it easy to attribute to them an experience of red and green – novel colours for the monkeys. Why? Because their vision has been made functionally, and perhaps physiologically, like that of human trichromats. So, we readily attribute experiences with which we are also familiar – that is, experiences of red and green – to Dalton and Sam.[40] Why, then, do we feel more resistance in doing so for cDa29 and other tetrachromats, whose behaviour, we have seen, is consistent with seeing novel colours, and where a similar physiological process to that undergone by the monkeys has likely occurred, involving, in part, the development of a new opponent processing channel?

I suggest that we are inclined to withhold attributing experiences of novel colours to tetrachromats because we have never seen such colours ourselves. That is to say, we allow chauvinism to affect our judgment. As a trichromat oneself, and as part of a majority population of trichromats, one readily – too readily – assumes that one's own colour experiences give the appropriate basis for understanding the limits of colour experience. Brought into the open in this way, it will be clear that this scepticism about novel colours is merely prejudice. How then can we find the right attitude? Perhaps this will help. Imagine if most humans were dichromats, and only a handful trichromats. What would be the right way to treat the trichromats' colour experiences? It would be, of course, to affirm the reality of the colours they see – red and green – even though we, along with a large part of the popula-

[40] Although we easily think that the monkeys see red and green much as we do, Jay Neitz and Maureen Neitz do not assume this: "[G]ene therapy has successfully allowed red–green color-blind monkeys to see new colors that they have never seen before, [but] we still don't know what their internal perceptions of those colors are like." (neitzvision.com) In a popular article, vision researcher Joseph Carroll fills out this idea: "The ability to discriminate certain wavelengths arose [in the monkeys] out of the blue, so to speak – with the simple introduction of a new gene. Thus, the [brain] circuitry there simply takes in whatever information it has and then confers some sort of perception." (Quoted in Wolchover, 2012)

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tion, had never seen them and found them unimaginable.[41] That, in effect, is our current situation in relation to tetrachromats and their experience. Our membership of a majority who happen to be blind to certain colours should not bar us from affirming their reality.[42]

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[41] Hardin (1993, p. 146) makes much the same point. Jackson (1982), discussing his thought experiment involving an individual, Fred, who can see a novel colour, puts the idea vividly: "We are to Fred as a totally red–green colour-blind person is to us. H. G. Wells' story 'The Country of the Blind' is about a sighted person in a totally blind community. This person never manages to convince them that he can see… [t]hey ridicule this sense as quite inconceivable … . We would be making their mistake if we refused to allow that Fred can see one more colour than we can." (p. 129)

[42] I can suggest one other way of addressing residual scepticism. I see no reason why gene therapy, similar to that undergone by the squirrel monkeys, could not be practised on humans. Indeed, Jay Neitz and Maureen Neitz advocate for treating human colour-blindness in this way. (neitzvision.com) It would seem a relatively simple matter to adjust such a treatment to give adult human subjects a fourth cone. Dalton's and Sam's visual systems adapted in five months to process the new inputs they received. Given a suitably rich fund of visual stimuli, the human visual system may well adapt in a similar way. That is, it could be a straightforward process to transform a trichromat human subject into a tetrachromat, able to experience novel colours for themselves, and compare their trichromat experiences with their newfound tetrachromatic vision. For the sceptic brave enough to undergo that treatment, it would be a most effective antidote for doubt about novel colours.

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