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A Methodology for the Prediction of Complementary Colours in Chromatic Afterimages

José María González Cuasante, Fernando Alonso Muñoz, María Cuevas Riaño

Abstract

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After steady and prolonged perception, colours lose their initial strength due to a partial adaptation of the visual receptors. Under these circumstances the appearance of colours tends toward a neutral point, an achromatic grey equidistant to black and white. If the gaze is then directed towards a white or grey surface, the previous loss of chroma causes the complementary tone.

To precisely determine the tone, clarity and chroma of afterimages seen on an achromatic surface, a model using equalisation tests compares their effect with an appropriately chosen sample colour. In many cases, after 20 seconds of fixed perception, the comparison sample results in a colour of complementary additive tone with a saturation of half the original sample and an inversion of clarity equivalent to the loss or gain in the adaptation colour. For this comparison sample to be reliable, it should not be affected by the border colour of the original sample. To this end, a medium grey that does not create an afterimage on the comparison sample is juxtaposed.

The study shows that reds and greens give the expected results. However, yellows and blues give afterimages that deviate toward purples and oranges. The more saturated the yellows and blues are, the more severe is this effect.

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II. Colour & the Mind

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Introduction

The relationship between chromatic afterimages and successive contrast has always been an intriguing topic and has been dealt with together with induction and other simultaneous contrast effects. There are many studies on the related fields of simultaneous contrast, the perception of borders, receptive fields, lateral inhibition and chromatic adaptation. However, there are few studies that deal with chromatic afterimages specifically. This study does not seek to close the debate on this topic. The tests presented in this article are empirical, and their purpose is to provide material that can be used to improve scientific reflection.

Interest in changes in colour sensitivity may go as far back as Purkinje, who differentiated between photopic and scotopic vision, and later to Von Kries, whose coefficient law accounted for colour constancy in the human visual system. More recent colour research has focused on establishing colour appearance models (CAM),[1] since for perception the permanent characteristics of objects are more important than the characteristics of the light sources that make them visible. The perception of “constancy” under different lighting conditions requires certain processes of chromatic adaptation. This is the subject of scientific research into chromatic adaptation transforms (CAT).[2]

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[1] Mark D. Fairchild, *Color appearance models* (New York: John Wiley & Sons, 2005).

[2] Mark D. Fairchild, “Chromatic Adaptation and Color Appearance” (PhD diss., University of Rochester, 1990); Mark D. Fairchild and Peter Lennie, “Chromatic adaptation to natural and incandescent illuminants,” *Vision Research* 32, no. 11 (November 1992): 2077-2085, https://doi.org/10.1016/0042-6989(92)90069-U; Fairchild, *Color appearance models*; Annette Werner, Lindsay T. Sharpe, and Eberhart Zrennerb, “Asymmetries in the time-course of chromatic adaptation

These facts are taken into account and it is clear that the chromatic transformation of adaptation is essential for the perception of constancy. But it should be remembered that proper recognition of the visual field is done through continuous eye movements that are rarely interrupted. Fixing one's gaze on one point for a time often leads to a feeling of discomfort, though one continues to see normally.

Due to partial adaptation, a fixed and prolonged gaze throws off the proper discharge of the receptors to the general lighting conditions (chromatic adaptation) and affects the appearance of the focalized stimulus and the background equally.

In matching the appearance of afterimages with colour samples, the first difficulty arose in the physical area for comparison due to inevitable simultaneous contrast. Most examples given in manuals consist of an isolated colour sample on a white background, and the afterimages are meant to be seen on that same white background. This does not account for the fact that the colour sample is darkened due to simultaneous contrast with the white of the background. Once the subject has adapted to the white, the afterimage tends to be perceived as bright on a grey background.[3] Placing the comparison sample next to the area where the subject's gaze rests is ineffective, because when the gaze is turned to the sample, the adaptation to the previous white background will darken the sample, and it becomes practically impossible to see the two colours as equal. The use of a medium grey prevents these problems.

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and the significance of contrast," *Vision Research* 40, no. 9 (April 2000): 1101-1113, https://doi.org/10.1016/S0042-6989(00)00012-2; Annette Werner, "Spatial and temporal aspects of chromatic adaptation and their functional significance for colour constancy," *Vision Research* 104, no. 1 (November 2014): 80-89, https://doi.org/10.1016/j.visres.2014.10.005; Mary Hayhoe, and Peter Wenderoth, "Adaptation Mechanisms in Color and Brightness," *From Pigments to Perception. Advances in Understanding Visual Processes* 203, no. 1 (1991): 353-367, https://doi.org/10.1007/978-1-4615-3718-2_41.

[3] David R Williams, and Donald I. A. MacLeod, "Interchangeable backgrounds for cone afterimages," *Vision Research* 19, no. 8 (1979): 867-87, https://doi.org/10.1016/0042-6989(79)90020-8.

1. Average value grey

When partial adaptation due to prolonged vision occurs, an initially white stimulus will lose intensity and become grey. By the same token, an initially black stimulus will become lighter. Both stimuli tend toward a medium grey. In Figure 1 a medium grey is juxtaposed between white and black in order to see how the white and grey evolve after 20 seconds of adaptation. The lower area shows a light grey juxtaposed with white, and a dark grey juxtaposed with black. Comparison for a time renders the white similar to the light grey and renders the black similar to the dark grey.

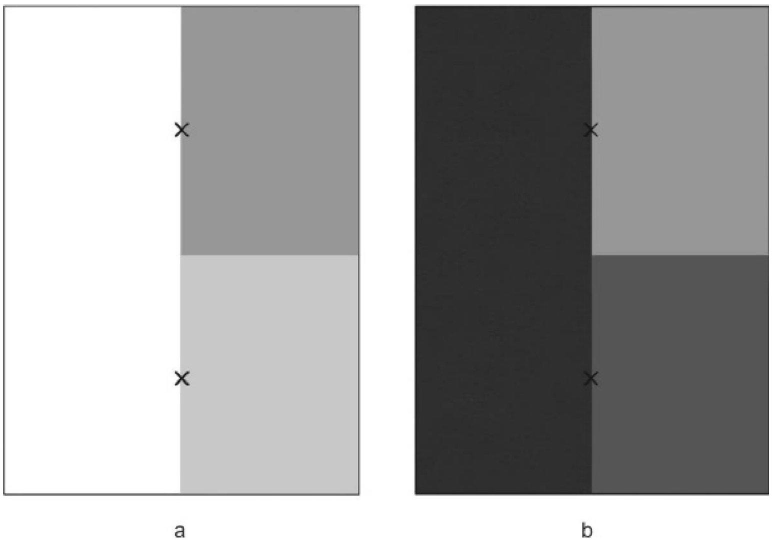

Figure 1: a) Stare at the upper x for 20 seconds. Next, stare at the lower x for 5 seconds. The appearance of the white region will be observed to approximate that of the juxtaposed light grey region.
b) The same process for the black region will produce a lightness similar to the juxtaposed dark grey.
Source: José María González Cuasante (research concept), Fernando Alonso Muñoz (graphic design).

Can these results be quantified? Various tests show that in 20 seconds of adaptation, the white (CIELab: L96) loses 16 points for a resulting value of 80, while the black (CIELab: L25) gains 20 points, reaching a value of 45. Next, the new value of CIELab: L80 again loses 16 points, resulting in a value of 64, while the dark grey (CIELab: L45) again gains 20 points for a new value of 65. Now the appearance of the two resulting greys is the same, as we can see Figure 2.

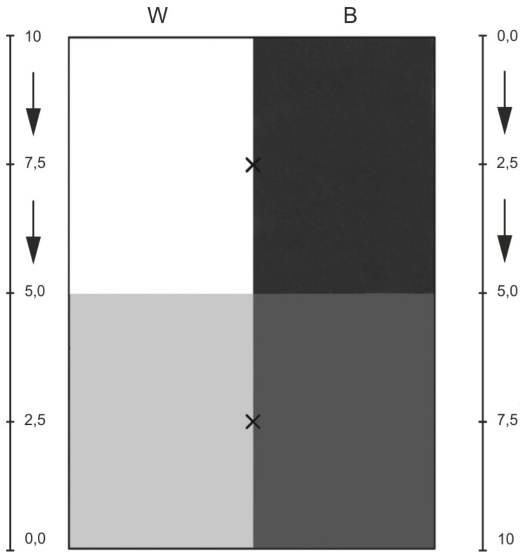

Figure 2: Simultaneous adaptation to black and white for 20 seconds causes the white to darken and the black to lighten. Then, when the eyes are set on the bottom point, the samples appear to match.
Source: José María González Cuasante (research concept), Fernando Alonso Muñoz (graphic design).

2. Proposed system

Based on these results, a grey of value CIELab: L64 was used, with the intermediate value between black and white as a reference to test other chromatic samples. Using grey during the initial observation phase is essential to properly guiding the determination of the complementary hue of the comparison samples, because a mid-value grey, as the point of convergence of all adaptations, is also the balancing point for all complementary inversions. Even more importantly, it has no adaptation-inducing effects; the response to such a stimulus remains static and does not cause any change in the comparison sample.

The system proposed as a model and put into practice is shown in Figure 3. The stimulus intended to induce adaptation is placed in zone 1. Zone 2 contains the chosen achromatic, mid-value grey, which does not undergo any transformation due to adaptation or induce any value or colour changes in the stimulus for comparison. The same grey as that in zone 2 is also placed in zone 3 to receive the afterimage generated in zone 1. Finally, a physical sample is placed in zone 4 to match against the appearance seen in zone 3, which does not undergo any alteration from previous adaptation to the grey in zone 2.

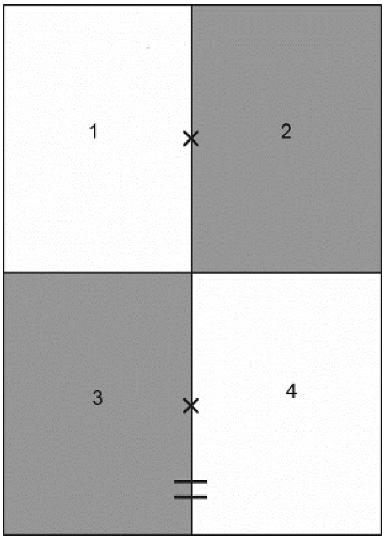

Figure 3: Model proposed to perceive the effect of the appearance on afterimages. In 1, the colour sample tested to produce the effect. In 2, a juxtaposed middle value grey. In 3, the same grey to perceive the effect produced by the adaptation of 1. In 4, the colour sample intended to match the effect perceived in 3.
Source: José María González Cuasante (research concept), Fernando Alonso Muñoz (graphic design).

All samples used are reflection stimuli, colour samples painted on card stock referenced in the CIELab colour space. (Photomechanical or digital reproduction can alter the original effects of the painted colours.)

To carry out the colorimetric measurements at CIELAB, a Konica Minolta CM 2600d spectrophotometer belonging to the Labmat of the Faculty of Fine Arts of the Complutense University of Madrid was used. This device works within a wavelength range of 400nm-700nm and a measurement range of 10nm. A standard illuminant D65, standard observer 10, optical reflection geometry (d / 8) and a measuring area diameter of 3mm was used. The colour data was taken with CM-S100w 1.91.0002 Spectra Magic software.

The four stimuli are presented head-on at approximately 50 cm and perpendicular to the view of the observers, who must only move their gaze from up to down following simple instructions. The colours used are painted on cards measuring 5.5 x 4 cm each. The tests were done in a neutral environment with natural lighting (standard illuminant

C or D65) and no reflections. No special devices or laboratory were necessary. The instructions given to the observers were the following:

1. The observers should not manipulate the tests or exchange the samples, which are presented to them exactly as planned after having tested them appropriately. They confirm or reject the equalization of the effect.
2. The process begins by clearing vision from its previous state by looking at a medium, neutral grey for a few seconds (L64).
3. Then the gaze is focused on the indicated point in the upper juxtaposition and held there for 20 seconds.
4. After this time, the gaze is lowered to the lower juxtaposition point and held there for five seconds to determine whether the appearance of both areas is equalized as expected.

To minimize the inevitable saccade effects that occur at the edges of the samples, the subject should be recommended that any involuntary eye movements should occur vertically along the juxtaposition line (horizontal movements affect how the afterimage that is seen later is generated and should be avoided).

Given the subtlety of the method, once the observers were appropriately trained, the results appeared to be quite satisfactory: of 35 male and 15 female fine arts students between the ages of 18 and 23, 85% responded favourably.

If the tests are performed by adjusting the colours on a computer screen following this same model, the results may differ, as the colours used are web emission colours.

A similar model also based on four colours was published by M. H. Wilson in 1955[4], with the aid of coloured discs with two different radii on two closely placed wheels, one for adaptation and the other for testing, to match the appearance effect. The perceived effects, although

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[4] Matthew H. Wilson, and R. W. Brocklebank, “Complementary Hues of After-Images,” *Journal of the Optical Society of America* 45, no. 4 (1955): 293–299, https://doi.org/10.1364/JOSA.45.000293.

fleeting, were similar to those experienced in this test, as were the conclusions.

Recent works, such as Riccardo Manzottis ‘A Perception-Based Model of Complementary Afterimages’[5], show some adjustments of the appearance, but the presented model is less vulnerable to a simultaneous contrast effect. Beginning with an assumption that quickly became a certainty, namely, that after 20 seconds of adaptation, the formed chromatic afterimages do not reach the chromatic intensity of their complementary opposites. If the test is performed on grey, then only half of this intensity is reached, just as is observed for black and white inversions. We believe that even if part of the signal of the most active receptors is lost during adaptation, then these receptors respond with low intensity to the neutral stimulus, but still respond.[6] However, since those that were less active respond with greater force, they cause the desaturated complementary tone to be perceived.

Figure 4 shows a theoretical scheme that illustrates the sensory development of a particular colour (A) during 20 seconds of adaptation (A´). On the other side of the brightness axis, following the direction of the arrow, is the point (P) at which the colour of the appearance of the afterimage on an intermediate grey sample (O) is assumed to lie in its value and chroma (the complementary assumption). In this example, the matching sample must have higher brightness than the medium grey on which the afterimage is perceived; its brightness must be increased to the same extent as that to which the initial stimulus was increased during adaptation.

While in 20 seconds of adaptation the colour normally loses half of its chroma, when the primary stimulus is very bright and saturated, the chroma loss is slightly higher.

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[5] Riccardo Manzotti, “A Perception-Based Model of Complementary Afterimages,” *Sage Journals* 7, no. 1 (January 2017): 1-10, https://doi.org/10.1177/2158244016682478.

[6] Johannes Von Kries, *Handbuch der physiologie des Menschen* (Brunswick: Vieweg, 1905).

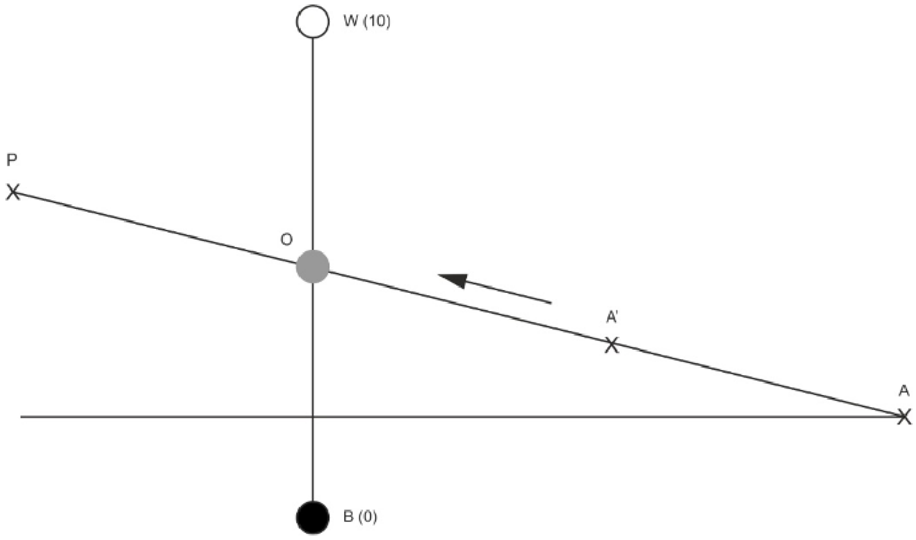

Figure 4: Theoretical model that represents the process of adaptation while the eyes are fixed on a coloured point for 20 seconds. Colour A desaturates in the appearance of A´. While staring at a sample of the desaturated colour, its appearance shifts towards grey (O). If the eyes then look at a grey sample, then the complementary hue (P) appears, with an increase in brightness in O that is equal to what has been gained during adaptation.
Source: José María González Cuasante (research concept), Fernando Alonso Muñoz (graphic design).

3. Complementary

The term "complementary" is used in different ways.[7] Often, the most correct use of this term refers to two colours that can be mixed to produce a neutral result (white, black or grey), i.e., two colours capable of cancelling each other out, in either additive or subtractive syntheses, without leaving remnants of the chroma of either colour. This is the most common usage in most colour specification models. But the term is also used to mean a colour that is "sensorially opposite" to another and which does not necessarily correspond to the tone that would be used to neutralize that colour. Goethe, in the chapter of his treatise on "physiological colours", elaborates on this sensory requirement to complete "totality" and repeatedly refers to coloured afterimages.[8] These complementary colours are the conventional ones known in the

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[7] Ralph W. Pridmore, "Complementary colors theory of color vision: Physiology, color mixture, color constancy and color perception," *Color Research and Application* 36, no. 6 (December 2011): 394–412, https://doi.org/10.1002/col.20611.

[8] Johann Wolfgang von Goethe, *Theory of Colours* (London: John Murray, 1840).

western phenomenological tradition and in the experience of artists: red-green, blue-orange and yellow-violet.[9]

Generally, colour representation systems organize the opposite hue according to the concept of complementary colours that the systems use. Colours that result in white or grey after being mixed are considered complementary according to the colourimetric models obtained from matching tests. In the CIE 31 triangle (Figure 5), complementary colours oriented towards their dominant wavelengths are connected through the equal energy white. If both ends of such a connection are mixed (for example, a 580 nm yellow with a 480 nm blue or a 610 nm red with a 492 nm blue green), then the same white is produced.

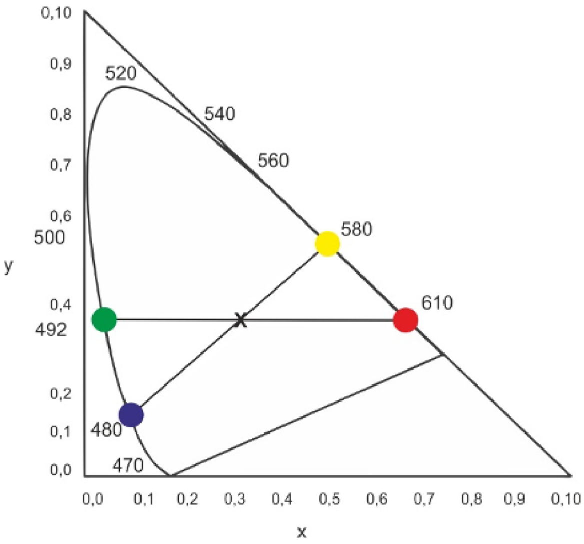

Figure 5: Additive complementary colours represented in CIE 31: red at 610 nm with bluish-green at 492 nm and yellow at 580 nm with blue at 480 nm.
Source: José María González Cuasante (research concept), Fernando Alonso Muñoz (graphic design).

Additive complementary colours come from mixtures of this type: between a colour and white in order to desaturate, or between opposite colours in order to yield grey. That condition determines a quality belonging to complementary colours projected in a straight line through the centre to yield white or grey. However, afterimages sometimes coincide, and other times do not.

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[9] Eugène Delacroix, *Eugène Delacroix: Journal 1822-1863* (Paris: Librarie Plon and Centre National des Letters, coll. Les Memorables, 1981); Johannes Itten, *Art de la couleur* (Paris: Dessain et Tolra, 1996).

The afterimages are not the result of mixing the adaptation state of a particular colour with that reflected on the new observation field; rather, they are simply the momentary responses of the receivers S, M and L to that new field.

Tests began with complementary additives. The Munsell (1946) colour chips[10], which are based on the work of James Clerk Maxwell[11] and Ogden Nicholas Rood[12], can be used as physical samples to predict the appearance of the colour in its three dimensions of hue, value and chroma when a match is expected. However, because the colours required for matching are often very precise and require greater accuracy, in many cases, coloured discs are used. It is not difficult to determine each colour point in a Maxwell triangle using two sets of discs with different radii and to specify the brightness coefficient as well.[13] Having achieved the required colour, it was reproduced materially by painting, to serve as a sample for matching afterimages. With two-radius discs the tone and value of any saturate can be determined. Chroma are only out of alignment when their distance from the centre does not correspond to their true value (Figure 6). Therefore, colour measurements were taken from the CIELab model, where the chroma determination fits well with the experimental tests.

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[10] Albert Henry Munsell, *The Munsell Book of Color* (Baltimore: Munsell Color Company, 1946).

[11] James Clerk Maxwell, “Experiments on colour as perceived by the Eye with remarks on Colour Blindness,” *Proceedings of the Royal Society of Edinburgh* 3, no. 45 (1857): 299-301, https://doi.org/10.1017/S0370164600028224.

[12] Ogden Nicholas Rood, *Modern chromatics: students’ text-book of color with applications to art and industry* (New York: Van Nostrand Reinhold, 1973).

[13] José María González Cuasante, *El color de la pintura. Teoría de las mezclas cromáticas y su representación* (Madrid: Hermann Blume, 2008).

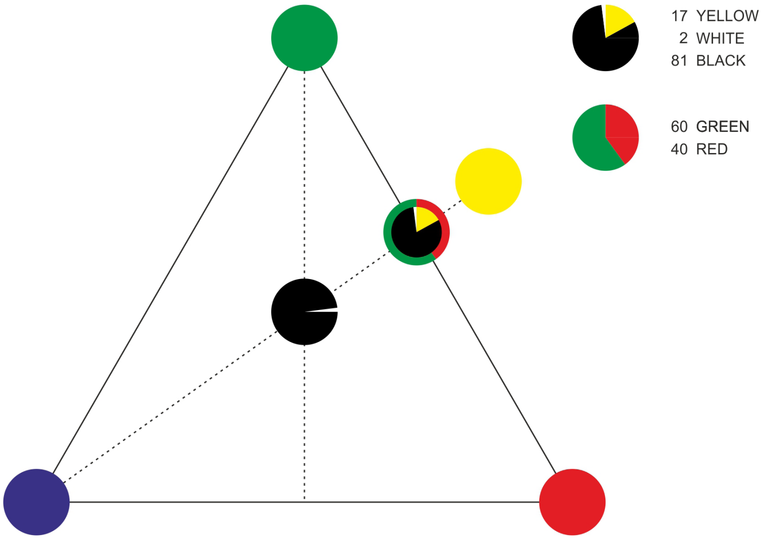


Figure 6: Representation of the colour yellow in a Maxwell triangle. R+G = Y + Bk, where the angle of the hue and the brightness of the yellow are determined, but not the dimension of the chroma.
Source: José María González Cuasante (research concept), María Cuevas Riaño (graphic design).

3.1. Red and green

The inversions of reds and greens usually fit with the predictions of the complementary additives because the painted samples used are not too saturated (very saturated emission reds can deviate). Figure 7 shows the chroma loss of a red (CIELab: L47 a52 b34) juxtaposed with a medium value grey (CIELab: L64) after 20 seconds of adaptation. During that time it becomes what is seen when one's gaze is lowered in the same figure (Figure 7-a). The feeling of red becomes equal to an unsaturated sample achieved through an averaged optical mix using red, white and black discs that is later imitated with paint, whose brightness is equal to that supposedly attained by the red through adaptation and half its chroma (CIELab: L58 a26 b12). The same red reverted on the desaturated sample momentarily produces a grey impression; the interpretation of this phenomenon is that once the red has lost half of its chroma, if this loss is projected onto a sample with the same red hue at half the saturation, the chroma is totally lost (Figure 7-b). By the same mechanism, the afterimage projected on grey (L65) appears as the bluish green additive complementary colour but with less chroma because of the response on the grey sample from the receptors that experienced more loss (CIELab: L74 a-35 b-8) (Figure 7-c). In all three examples, the retinal receivers developed in the same way during adaptation, suffering identical sensory losses; therefore, the effects of afterimages also depend on the new stimulus on which they are projected.

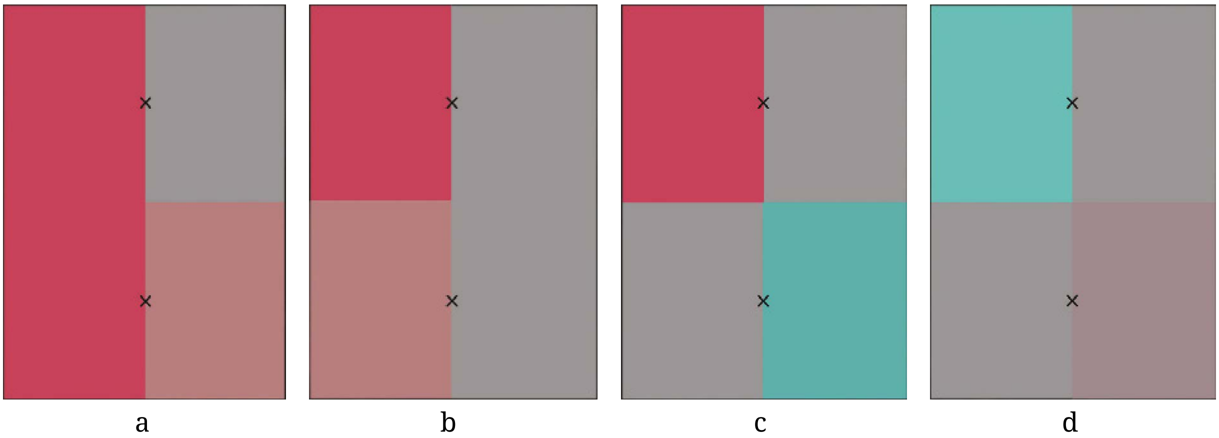


Figure 7: a) When the viewer's eyes are set on the point above for 20 seconds, the adaptation to red transforms the perception of the colour into the desaturated colour seen when the viewer looks down to the point below. b) The same adaptation to red, seen immediately afterwards on a physical sample of desaturated red, produces the appearance of grey. c) If the adaptation to red is seen on grey, the afterimage appears bluish green (the colour with which an additive mixture would result in grey). d) The afterimage of bluish green, seen on grey, results in a very desaturated red colour on the same hue line as the previous red.
Source: José María González Cuasante (research concept), Fernando Alonso Muñoz (graphic design).

The anticipated colours are even more accurate when working with bluish-green. This green produces complementary impressions with the same hue as the previous red; however, because it has half the saturation of the previous red and then half of its own saturation is lost, this adaptation results in afterimages with a quarter of the saturation of the initial red (CIELab: L62 a14 b4) (Figure 7-d).

Figure 8 shows how the blue-green colour is represented in a Maxwell triangle in an equalization between two sets of discs: the optical mixture of the three primary colours and that of blue-green with black. The blue-green has a brightness superior to the level of the grey by as much as the red gained through adaptation, and a lower saturation equivalent to half. The increased brightness of the colour is similar to the one shown in Figure 4.

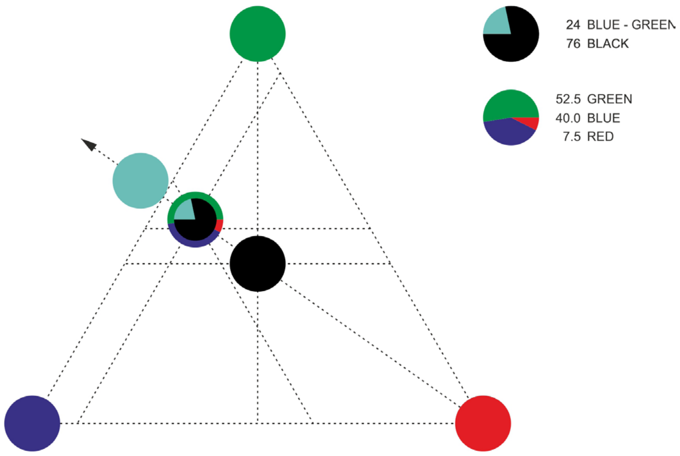
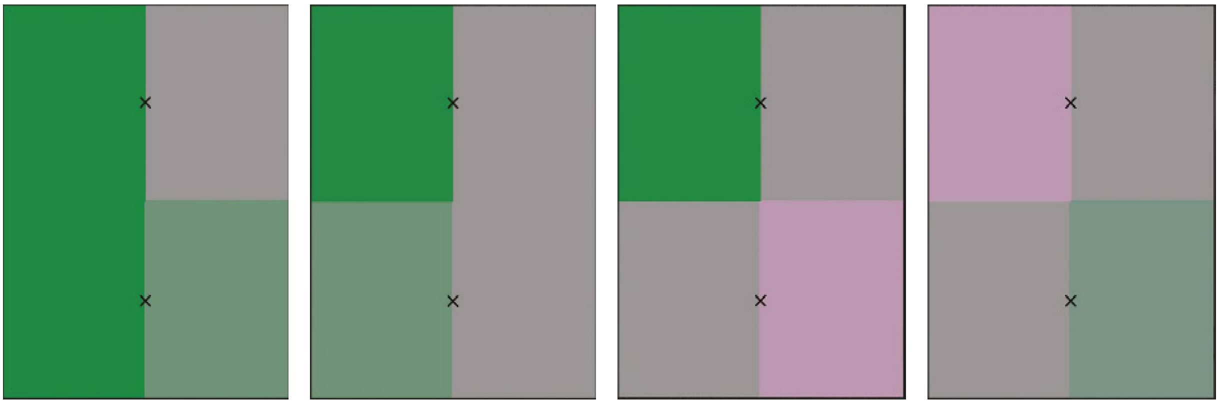


Figure 8: The optic mixture of the primary colours blue, green and red is equivalent to the mixture of black and blue-green (B+G+R=Bk+Blue-Green). Since black emits little reflection, the small portion of blue-green is practically equal to the brightness of blue + green + red (B+G+R). Therefore, its colour is slightly more than three times as bright as the primaries.
Source: José María González Cuasante (research concept), María Cuevas Riaño (graphic design).

Greens with peaks from 495 nm to 565 nm have the colours magenta and purple, which are not on the spectrum, as additive complementaries; in all of these cases, the two types of complementaries match. The green shown in Figure 9 (CIELab: L55 a-50.5 b 28.5) is inverted on grey with a pink additive complementary (CIELab: L67.36 a21 b-13.5) (Figure 9-c). The afterimages of the colours on the line of purples and magentas also do not deviate from their greenish complementaries (Figure 9-d).



a b c d

Figure 9: a) The adaptation to green for 20 seconds results in the loss of half of the chroma (CIELab: L 58 a-13 b6). b) If the eyes look at the desaturated colour after adaptation, then grey is seen. c) If the viewer looks at the grey, a desaturated complementary pink is observed (the colour with which an additive mixture would result in grey). d) The afterimage of the pink above seen on grey is a very desaturated version of the green above (CIELab: L 61 a-12 b4).
Source: José María González Cuasante (research concept), Fernando Alonso Muñoz (graphic design).

3.2. Yellow and blue

If similar tests are performed with yellows, then the effects cannot be anticipated with the same predictability, and matching tests become absolutely indispensable because of these irregularities. If a yellow oriented at 580 nm (CIELab: L85 a4 b90) is observed, its hue line is desaturated more than expected (CIELab: L75 a0.25 b23) (Figure 10-a). However, if the viewer looks at the desaturated physical sample after adaptation, they see not a perfect grey, but instead a shade that is shifted slightly towards the violets (CIELab: L65 a2.75 b-15.4) (Figure 10-b). This hue deviation already predicts mismatches with respect to the additive complementary.

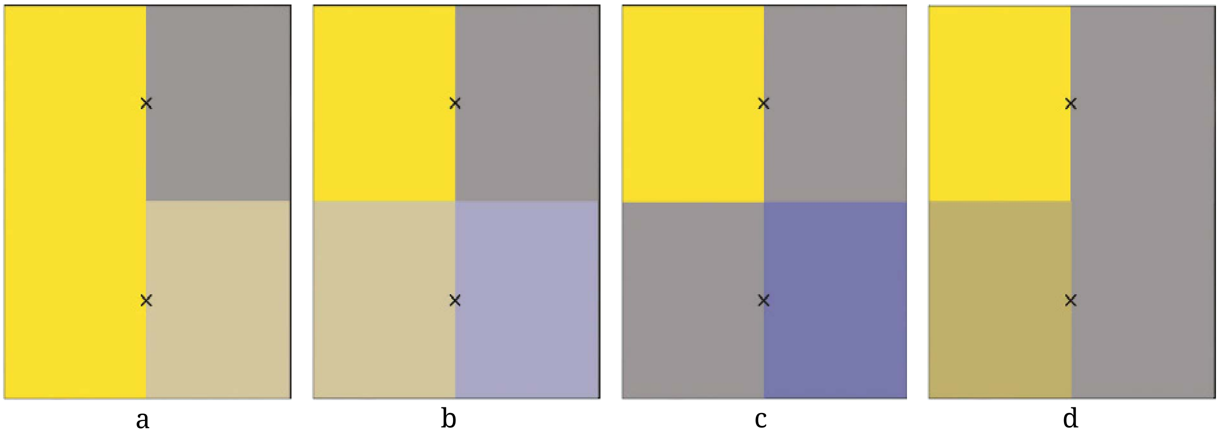


Figure 10: a) The adaptation to yellow for 20 seconds produces a strong loss of chroma. b) On a physical sample of the desaturated yellow, the afterimage does not appear grey, but rather is a shade that tends towards purple. c) The adaptation to yellow as seen on grey results in a violet blue colour that deviates from the additive complementary (an additive mixture with this colour would not result in grey). d) For the original yellow image to produce a grey afterimage, the eyes must look at a greenish yellow.
Source: José María González Cuasante (research concept), Fernando Alonso Muñoz (graphic design).

This mismatch can be better demonstrated by looking at the middle-value grey. The necessary matching sample required is not derived from the blue, with which a mixture would result in grey; instead, it is a more violet blue (CIELab: L60 a7 b-35) (Figure 10-c). For the afterimage of the yellow to appear grey, it must be projected on a desaturated greenish yellow, which momentarily offers a sensory balance in the response (CIELab: L73 a-5 b54) (Figure 10-d), because the violet blue of the afterimage will be cancelled out by the greenish-yellow colour of the base. The determination of the hue line of this greenish yellow colour and its extension through the centre indicates the hue orientation of the violet blue afterimage produced by the yellow (CIELab: L60 a7 b-35). Evidence seems to indicate that a reddish component, apparently supplied by the S cones, prevents matching with the blue additive complementary, and the comparisons must be performed using samples with more purple hues.

While testing blues with a hue near the afterimage of yellow, some deviations are found, although they are not as pronounced. The blue in Figure 11-a is the violet blue of the afterimage of the previous yellow (CIELab: L60 a-7 b-35) (Figure 10-c), which is measured at 470 nm. The afterimage it projects on grey is light, very grey and greenish yellow, with little deviation from the additive complementary (CIELab: L73 a-3 b-20). The deviations are observed as higher if the colours have more chroma, and if the colours have less chroma, then they are approaching the complementary additives, as is seen in this case.

A blue measured at 475 nm (CIELab: L46 a9 b-45), which is not the additive complementary of our yellow, produces highly desaturated afterimages of that concrete yellow (CIELab: L64 a2 b18) (Figure 11-b). Another blue, with the same hue orientation but less saturated (CIELab: L50 a5 b-30), produces slightly green afterimages that match the additive complementary hue (CIELab: L65 a-1 b14) (Figure 11-c). However, if we try a more saturated blue on the same hue line (CIELab: L45 a13 b-70), then the afterimage looks not only more saturated, but also more orange (CIELab: L68 a9 b21). (Note: Photomechanical limitations prevent the proper representation of this type of blue.) In fact, these three blues with the same colour orientation have different appearances: the most saturated looks bluer, and the least saturated looks more violet. This finding reinforces the assumption of what seems obvious: appearance serves as a better basis than hue line for anticipating afterimage effects. Figure 12 shows the CIELab representations of the colours in Figures 10 and 11.

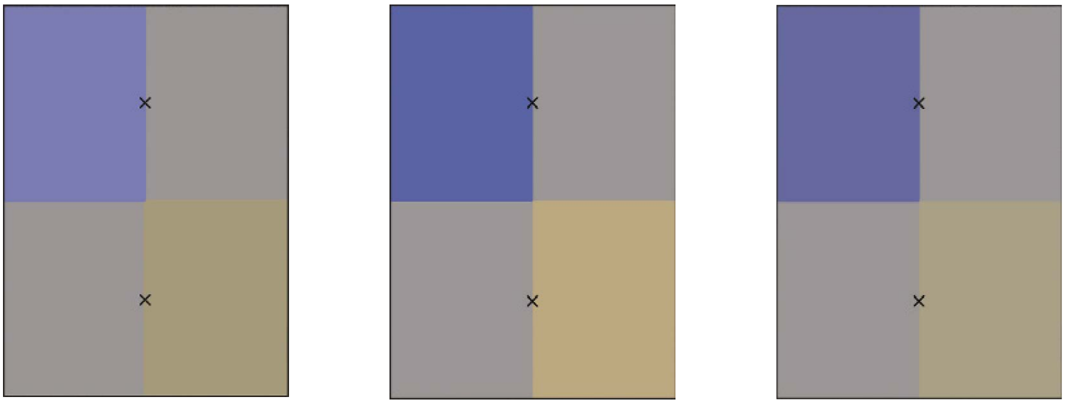


Figure 11: a) After 20 seconds of adaptation, the violet blue in Figure 11-c, which is measured at 470 nm, produces a very desaturated afterimage that is close to the additive complementary when seen on grey. b) The afterimage of a blue measured at 475 nm, when seen on grey, shows a desaturated colour on the same hue line as the yellow in Figure 10. (The additive mixture would not result in grey.) c) A more desaturated blue on the same hue line (475) produces an afterimage of the complementary greenish yellow hue when seen on grey.
Source: José María González Cuasante (research concept), Fernando Alonso Muñoz (graphic design).

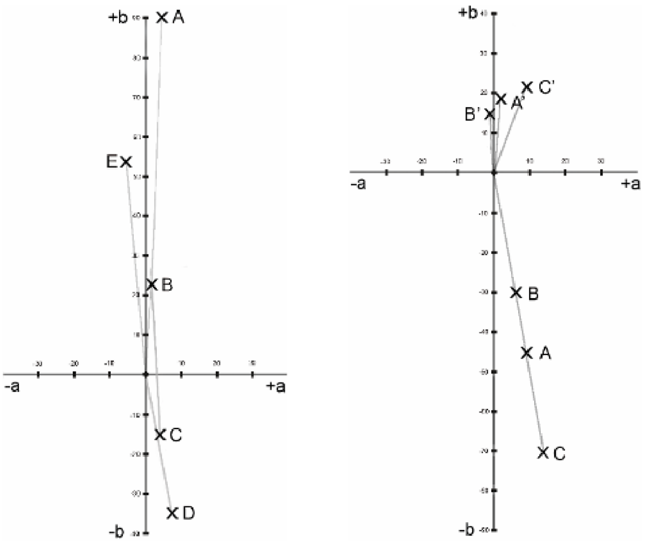
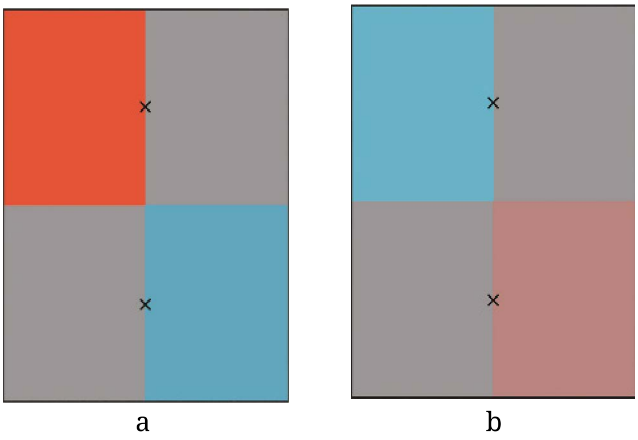


Figure 12: a) CIELab representation of the colours in Figure 10: yellow (A); desaturated yellow (B); afterimage of the yellow seen on desaturated yellow (C); afterimage of the yellow seen on grey (D); greenish yellow colour that is required for the afterimage of the yellow to appear grey (E).
b) Representation of the blues from figures 11b & 11c. The colour A on grey, produces the appearance of A’. The colour B produces the colour B’. The colour C, a saturated blue (not represented in this work), produces the colour C’.
Source: José María González Cuasante (research concept), Fernando Alonso Muñoz (graphic design).

3.3. Orange and cyan

As is the case with yellows and reds, in oranges (CIELab: L62 a52 b62) the desaturation due to adaptation occurs along the hue line, but its afterimages are perhaps the ones that diverge the most. Cyan comparison samples require hues with somewhat shorter wave lengths than those of additive complementaries (CIELab: L69 a-25 b-21) (Figure 13-a). Deviations are reduced as oranges approach red.

Those same blue hues of lower chroma are inverted in oranges with hardly any deviation (CIELab: L64 a15 b13) (Figure 13-b). All the bluish appearances that don't clearly display greenish or reddish nuances give orangish afterimages, independent of their wavelength.



a b

Figure 13: a) The afterimage of orange on grey results in a cyan hue that deviates from the additive complementary. (The additive mixture would not result in grey.) b) Afterimage of the before cyan on grey hardly deviates from complementary additive.
Source: José María González Cuasante (research concept), Fernando Alonso Muñoz (graphic design).

Discussion

The sensory tests undertaken show that complementary colours do not always correspond with additive colours. These discrepancies have hardly been studied, because articles dealing with afterimages have considered afterimages to be determined mainly by simultaneous contrast, which indeed also affect successive contrasts.[14]

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[14] F. Shively, "A new afterimage (color contrast afterimage?)," *Perception and Psychophysics* 13, no. 3 (October 1973): 525-526, https://doi.org/10.3758/BF03205814; Stuart M. Anstis, Brian J. Rogers, and Jean Henry, "Interactions between simultaneous

Successive contrast is the result of partial adaptation to the colour of each area of the observed field due to prolonged viewing. Regarding adaptation to illumination, Von Kries has already shown that the responses of receptors are inversely proportional to the intensity of the stimuli, and the same statement can be applied to chromatic adaptation and thus to different retinal areas. However, with regard to afterimages, rather than further investigating the weakening of the signal from the receptors[15] studies have focused on the effects of the partial adaptation related to the background (simultaneous contrast) and the consequent changes in appearance.[16] The most recent studies still discuss the instability and change in appearance caused by the background context and the sudden unevenness in luminance at the border.[17]

The differences between simultaneous and successive contrast are marked. In simultaneous contrast, the edge is neatly trimmed, and

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contrast and coloured afterimages," *Vision Research* 18, no. 8 (1978): 899-911, https://doi.org/10.1016/0042-6989(78)90016-0.

[15] Charles Arthur Padgham, "Afterimages as Means of Investigating Rods and Cones," *Ciba Foundation Symposium – Colour Vision: Physiology and Experimental Psychology* 1, no. 1 (January 1965): 249–264, https://doi.org/10.1002/9780470719404.ch13; Olga Eizner Favreau, and Michael C. Corballis, "Negative Afterimages in Visual Perception," *Scientific American* 235, no. 6 (December 1976): 42–48, https://doi.org/10.1038/scientificamerican1276-42.

[16] Anstis, Rogers, and Henry, "Interactions between simultaneous contrast and coloured afterimages," 899-911; John Krauskopf, Qasim Zaidi, and Marc B. Mandler, "Mechanisms of simultaneous color induction," *Journal of the Optical Society of America* A 3, no. 10 (1986): 1752–1757, https://doi.org/10.1364/JOSAA.3.001752; Oliver Rinner, and Karl R. Gegenfurtner, "Time course of chromatic adaptation for color appearance and discrimination," *Vision Research* 40, no. 14 (June 2000): 1813-1826, https://doi.org/10.1016/S0042-6989(00)00050-X; Qasim Zaidi, Robert Ennis, Dingcai Cao, and Barry Lee, "Neural Locus of Color Afterimages," *Current Biology* 22, no. 3 (February 2012): 220–224, https://doi.org/10.1016/j.cub.2011.12.021; Mitsuo Ikeda, and Chanprapha Phuangsuwan, "Strong effect of the simultaneous color contrast in an afterimage," *Color Research and Aplication* 44, no. 1 (2019): 50-53, https://doi.org/10.1002/col.22278.

[17] Georgie Powell, Aline Bompas, and Petroc Sumner, "Making the incredible credible: Afterimages are modulated by contextual edges more than real stimuli," *Journal of Vision* 12, no. 17 (September 2012): 1-13, https://doi.org/10.1167/12.10.17; Ikeda, and Phuangsuwan, "Strong effect of the simultaneous color contrast in an afterimage," 50-53.

lateral inhibition accentuates the perceptual differences in luminance, although consistency simultaneously pulls the perceived appearance back towards the physical conditions of the reflectance index of the observed surface. This way, objects can be distinguished from the background, but they do not deceive us.

In successive contrast, the aftereffects are afterimages with blurred edges, and because they are observed on surfaces different from those that generated them, they can be regarded as abnormal perceptions, or pure sensory appearances of ghostly effects. These afterimages can momentarily disturb, but do not deceive us. Certainly, the same hue changes its appearance on different background colours, taking on a hint of the shade that is complementary to the background in each case.[18] This is caused by the same physiological mechanism of lateral inhibition, which allows us to better differentiate colours. In addition, when the eyes look at a neutral (white or grey) surface after a period of adaptation with the eyes not moving and perceive the complementary inversions of the afterimages, the viewer also necessarily sees a new figure-background relationship, in which the sensory effects induced are even stronger because they lack consistency.[19] This means that the same yellow in red and green surrounding fields will be observed later as afterimages that are more purple surrounded by greenish blue and more blue surrounded by reddish grey, with respect to Figure 14 below, an effect resulting from the simultaneous contrast of the receptors occurring in ganglionic and bipolar cells.

The appearance of afterimages depends on three conditions: first, the adapted and weakened response to the stimulus; second, the simultaneous contrast of the field inducing the adaptation and third, the surface of the test field. In the example above, the question is whether the sensory differences in the appearance of the same stimulus are derived from different patterns of development of the discharges of the receptors and the subsequent cells during adaptation

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[18] Rinner, and Gegenfurtner, "Time course of chromatic adaptation for color appearance and discrimination," 1813-1826; Ikeda, and Phuangsuwan. "Strong effect of the simultaneous color contrast in an afterimage," 50-53.

[19] Anstis, Rogers, and Henry, "Interactions between simultaneous contrast and coloured afterimages," 899-911.

or simply from the new figure-background relationship that we see in the afterimages.

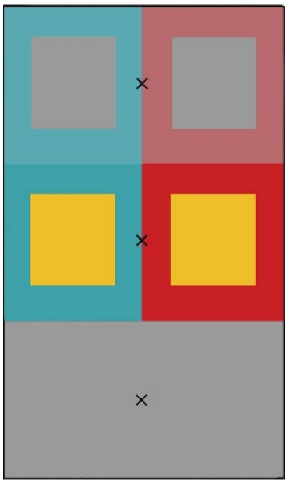

Figure 14: The same yellow suffers different inducing effects if surrounded by green instead of red, altering its appearance through simultaneous contrast. When surrounded by green, it looks a little more orange, and when surrounded by red, it looks greener. Its immediate afterimages on the grey field below look more purple when the initial surroundings are red and when the initial surroundings are green. In these cases, afterimages are conditioned by their respective backgrounds. If the perception of the afterimages is observed on the desaturated fields above, then the blue looks the same in both cases because the appearances of the background are also the same.
Source: José María González Cuasante (research concept), Fernando Alonso Muñoz (graphic design).

Returning to Figure 14, if the viewer's gaze is turned to the upper part after 20 seconds of observation, the afterimages of the yellow are the same violet-blue tone, with backgrounds of the same grey. In this case, the adaptation of the green and red backgrounds has been diminished, and on resting one's gaze on the same desaturated tones, greys are seen, as explained in Figure 7b. The afterimage of the yellow is not affected by the appearance of different backgrounds and therefore is the same. This allows one to disregard the effect of the background and focus more attention on the adaptation of the receptors and the conditions of the stimulus on which this adaptation is projected, thereby relegating the simultaneous contrast to a secondary determining factor.

Traditionally, trichromatic theory assumes that each of the three cones responds mainly to stimulation from a different one of three overlapping major areas of the visual spectrum.[20] Although this assumption explains very clearly the phenomena that occur after a period of adaptation and is still useful, subsequent studies do not recommend adhering too strictly to the sensory attribution of colours to the S, M and L receptors because the absorption peaks of the cones do not match with the purest appearances of the colours.[21] (Figure 15) Although the absorption of the cones predicts important properties of colours,[22] the appearance of the colour in each area of the spectrum does not seem to be an exclusive characteristic of the receptors, and undoubtedly, other physiological mechanisms also

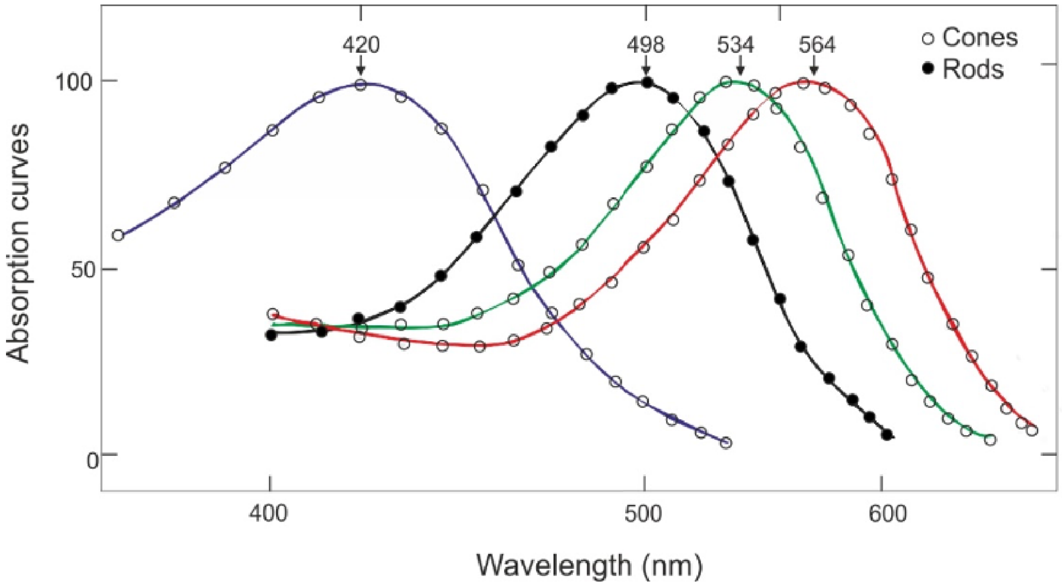

Figure 15: Absorption curves of the S, M and L cones according to J.K. Bowmaker-H.J. Dartnall (1980).

Source: José María González Cuasante (research concept), Fernando Alonso Muñoz (graphic design).

Based on: Bowmaker, James K., and H. J. A. Dartnall. 1980. "Visual pigments of rods and cones in human retina". Journal of Physiology 298: 501–511.

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[20] Hermann Von Helmholtz, *Helmholtz's Treatise on Physiological Optics* (Rochester, New York: Optical Society of America, 1924).

[21] James K. Bowmaker, and H. J. A. Dartnall, "Visual pigments of rods and cones in human retina," *Journal of Physiology* 298, no. 1 (January 1980): 501–511, https://doi.org/10.1113/jphysiol.1980.sp013097.

[22] Brian A. Wandell, "The cone spectral absorption functions predict important color properties," in *Foundations of Vision*, ed. Brian A. Wandell, (Sunderland, Massachusetts: Sinauer Press, 1995), 45-50 and 69-97; Semir Zeki, Samuel Cheadle, Joshua Pepper, and Dimitris Mylonas, "The Constancy of Colored After-Images," *Frontiers in Human Neuroscience* 11, no. 229 (May 2017): 1-8, https://doi.org/10.3389/fnhum.2017.00229.

contribute to the maximum sensitivity to or the final resolution of each colour.[23] Afterimages, which are mostly determined by the state of the receptors after adaptation, are perceived only at the end of a process that concludes when the optic nerve discharges in the brain.[24]

This is not a physiological study and the present goal is not to explain the latest cortical resolutions. Nor is the goal to link perceptions closely to the state of activity of cones. Rather, the purpose is to show some evidence of interest to questions of perception. Independently of what the receptors, optic nerve or brain do, it is clear that there is a somewhat reddish blue response at 470 nm and a yellow response at 580 nm.

The additive neutralization between yellow and blue that results in white or grey requires a certain amount of each colour to achieve cancellation.[25] A certain distribution of R, G and B between the two colours is required, and assuming that the yellow is produced by the M and L cones and is achieved by additively mixing G and R, it will be cancelled out by B, which in turn represents the signal coming from the S cones. However, if there is also a reddish contribution from the S cones, then it may leave a remnant, and a perfect grey will not be synthesized; therefore, the required blue in a synthesis must lack any reddish shade, and consequently, in additive or averaged mixtures, a peak at 480 nm is better than one at 470 nm.

These inherent qualities of synthesis do not coincide with the afterimage effects because they do not involve colour mixtures; instead, the visual system shows defective responses to newly experienced stimuli as a result of adaptation during prolonged exposure to a previous visual stimulus. To view the complementary effect well, it is necessary to look

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[23] Wandell, “The cone spectral absorption functions predict important color properties,” 45-50 and 69-97; Zeki, Cheadle, Pepper, and Mylonas, “The Constancy of Colored After-Images,” 1-8.

[24] Rob Van Lier, Mark Vergeer, and Stuart M. Anstis, “Filling-in afterimage colors betwen the lines,” *Current Biology* 19, no. 8 (April 2009): R323-R324, https://doi.org/10.1016/j.cub.2009.03.010.

[25] Leo M. Hurvich, and Dorothea Jameson, “An opponent-process theory of color vision,” *Psychological Review* 64, no. 6 (1957): 384–404, https://doi.org/10.1037/h0041403.

at a white or grey surface on which the most strongly adapted receptors will continue to respond with low intensity. As a consequence, these perceived colours have less saturation and, in the cases of yellows or oranges, the complementary colours shift slightly towards purple because the response of the S cones to the neutral stimulus better shows its own slightly violet nature and we tend to see a blue of 470nm instead of 480nm.

Conclusions

This study is especially focused on desaturation due to adaptation and on the correlation between the deviations and the degree of chroma (more than other studies that do not juxtapose the samples) and the physical material samples that match the observed effects are also specified.

In addition, when using a medium grey in the test and comparison fields, the inducing effects of simultaneous contrast disappear, and in general the tests yield positive results.

The main difficulty when applying the test is that prior training is required in order to keep perception fixed at a specific point for 20 seconds. Affirmative responses may be conditioned by the viewer's motivations and expectations as well as the degree of interest or indifference. Given the total precision required in the equalization effect and that the time of 20 seconds in some cases may not be the same, two types of answers were considered to be affirmative: equal and very similar. Two others were negative: not very similar and not at all similar.

Of the 850 responses collected, 719 were affirmative (84.6%) and 131 negative (15.4%), with a higher percentage of negative responses among men 78 (31%) than among women 53 (10%). There are no marked differences in the percentage of errors between different colours, but there are differences between the tests for each colour, with more successes in the comparisons with the complementaries than with their own desaturated samples.

In conclusion, it was found that practically all colours are weakened without leaving the additive tone line. An optical mixture averaged using discs that are white, black and of the colour in question, which run along the same additive line, can successfully match the desaturation effect caused by adaptation.

The physical colour of the previous additive mixture, which was then replicated with paint, is a desaturated hue with a trichromatic component that is obviously greater than when it is saturated; when looking at this colour after adapting to its saturation, sometimes grey is seen, and other times coloured greys are seen.

When the perceived result is completely grey, it is because there is a momentary balance in the sensory responses. That is, under those circumstances, in the case of the same hue but with little chroma, none of the hue is seen because the adaptation to saturation subtracts the little colour that remains from the desaturated colour. In these cases, the afterimage seen on grey matches the additive complementary.

When the result is not a perfect grey but is instead a certain neutral shade, the perceived hue is violet or reddish. The afterimage of the saturated colour does not completely neutralize the colour of the desaturated colour, and there is a reddish remnant. This result occurs when starting from yellows, oranges, a saturated blue or greatly saturated reds. These colours stray from the hue of the additive complementary colour, and this result is believed to occur because there are reddish sensations on both ends of the spectrum.

To produce grey from the afterimage of a saturated colour in such cases, the viewer's eyes must rest on a desaturated hue that is close but shifted in the opposite direction. In the case of yellow, a desaturated greenish yellow colour is required; and in the case of orange, a yellowish orange is needed. The additive opposites of these colours correspond to the sensory complementaries of yellow, violet-blue and of orange, cyan.

The afterimages of yellows and blues with less chroma progressively shift back to the additive complementaries and eventually match them completely when the colours are sufficiently desaturated, because in these cases, the adaptations affect all three receptors (S, M, L). Very saturated samples in emission colours tend to deviate in all cases. Recall, however, that this work focuses on relatively saturated paint samples whose reflective colours do not reach the brightness of emission colours.

The saturated colours from 570 nm to 610 nm result in the largest deviations. The complementaries of the reds at 610 nm remain virtually unaltered, but if they are very saturated, they could also undergo deviations. In the narrow region between 450 nm and 490 nm, the reflected colours generally have less chroma and therefore the deviations are smaller. The greens from 495 nm to 560 nm, whose additive complementaries lie on the purple line, do not result in deviations.

In addition, the colours not considered are those that Goethe called physiological to be the true complementary colours, as done by Wilson, who believes that unnatural deviations are inherent to additive processes. In the author's opinion, there are different types of complementary colours. The complementary additive colours mixing lights or reflections result in white or grey. The complementary subtractive mixing overlaying filters or mixing pigments, result in black. "Sensory complementaries" (afterimages) are not related to mixing or neutralization effects but instead represent the portion of the spectrum lacked by the colours that generated them, and thus, they are not recommended for mixtures. However, when colours are used as a means of artistic expression, then the complementaries that evoke the afterimages may be argued to respond better to aesthetic and emotional requirements, in addition to being popularly recognized as the most suitable.

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