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On the dimensionality of the colour world

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ABSTRACT

Whereas, for colorimetric purpose, the three-dimensionality of colour cannot be circumvented and clearly refers to cone fundamentals, we examine situations where a reduced or expanded dimensionality could be experienced. Besides the case of individuals such as dichromats who suffer from a limited number of cone photopigments and enjoy two-dimensional colour vision, specific contexts or specific operations may require additional dimensions which could be supported by rod signals or melanopsin signals.

1. INTRODUCTION

Since the seminal hypothesis of Thomas Young and the studies from Maxwell and Helmholtz during the 19th century, it has been firmly established that colour is three-dimensional. Physiological, psychophysical and genetic studies have confirmed the 19th century statements so that standardization bodies, colour industry, image technology have developed tools and methods to improve numerous colour products.

It is often claimed that the three dimensions of colour originate from the presence of three families of cones in the retina. Yet, the cone signals are processed within the retina and in the brain structures so that colour construction aims at identifying objects and materials in our surrounding. Colour vision starts with the capture of photons by the long-wave sensitive (LWS) cones, the middle-wave sensitive (MWS) cones and the short-wave sensitive (SWS) cones. At the second stage, retinal ganglion cells combine the cone signals into three channels: one achromatic channel, supported by the “magno-cellular” pathway where cone signals are added, and two chromatic channels, supported by the “parvo-cellular” and the “konyo-cellular” pathways where cone signals are opposed. Retinal signals are processed in the brain in various contrasting combinations, ultimately delivering highly tuned colour responses.

Whereas the three-dimensionality of colour is consensually accepted it is of interest to examine situations where the colour dimensionality could be reduced or expanded.

2. THE THREE-DIMENSIONAL CIE COLOUR SPACE

2.1 The cone fundamentals

The three colour dimensions hypothesis has been validated by Psychophysics much earlier than Physiology and Genetics has isolated cone families and sequenced the genetic code of cone pigments (Nathans et al., 1986).

As early as 1886, König and Dieterici were able to determine accurate spectral sensitivity of the fundamental sensations. By asking colour normal observers and dichromatic observers to perform colour-matches, they were able to derive spectral sensitivity curves of the fundamental sensations that conform the most recent proposals (Stockman and Sharpe, 2000).

CIE technical committee 1-36 was established for proposing chromaticity diagrams based on the best set of colour-matching functions and cone fundamentals available nowadays. Cone fundamentals are based on Stiles and Burch (1959) experimental colour matches and validated by Physiology. A physiologically designed MacLeod-Boynton chromaticity diagram (MacLeod and Boynton, 1979) is proposed as well as a cone-fundamental-based (x_F, y_F) chromaticity diagram. All data are now fixed (CIE, 2006; CIE, in press; Viénot and Walraven, 2007). Specifying colour in the LMS space will offer novel opportunities to solve problems of colour measurement and colour perception in everyday life and industry.

In the future, refinements, such as colour vision variability due to photopigment polymorphism, would not weaken the three-dimensionality hypothesis. It would secure the hypothesis.

2.2 Metamerism

Comparison between the richness of the spectral information available in the Physics domain and the reduced number of signals generated at the entrance of the visual system has led colour scientists to investigate at length the metamerism phenomenon.

In colorimetry, the basic experiment is a colour match between two metameric stimuli. Practically, colorimetry reduces the stimulus to a unique three component object. Indeed, the visual system is unable to finely analyse the spectral content of the stimulus. In the three-dimensional colour space, metamerism is just concealed.

Nevertheless the volume of ignored parts of the stimulus is amazing as illustrated by Kelly and Wyszecki (See figure 2(3.8.4) in Wyszecki and Stiles, 1982). It leaves room to numerous spectral power distributions with some remarkable properties.

3. SMALL DIMENSIONALITY COLOUR WORLDS

3.1 One or two photoreceptors (individual dimensionality)

3.1.1 Achromatopsia

Cases of one-dimensional colour vision are rare. Achromatopsia is a very rare case of inherited total colour blindness, mainly including blue-cone monochromacy with a relative occurrence of 1:100,000 diagnosed cases (Sharpe et al., 1999).

Achromatopsia cases with total loss of all three cone opsin genes have been well documented by Nordby (he is an achromat) and Sharpe who examined the society from Guam, an island in Micronesia, known from Oliver Sacks' book entitled "The Island of the Colorblind" (1997), where about 10% of the population suffers from inherited achromatopsia.

3.1.2 Dichromatism

Conversely, two-dimensional colour vision is common among mammals, apart from primates. In humans, dichromacy is well characterized. About 2% of the male population is dichromatic. Dichromacy is of genetic origin. Dichromats lack one family of cone pigments. It has been verified since 1986 by Nathans and colleagues that dichromats lack the corresponding gene sequence.

During the 20th century, dichromatic colour vision has been well documented, showing dichromatic Rayleigh matches. Hue discrimination is impaired around 590 nm for protanopes and deuteranopes, or around 490 nm for tritanopes. Colour appearance is

distorted. After a few reports from diagnosed unilateral dichromats, Judd (1948), Meyer and Greenberg (1988) and our group (Viénot et al., 1995; Brettel et al., 1997) have illustrated for the colour normal observer the colour appearance for dichromats.

The colour-blindness simulation is two-step.

In the LMS colour space, it is easy to find the colours that are confused by a dichromat. They lie on a line parallel to the axis corresponding to the missing fundamental. Our simulation was produced on a video-display, Cathode-Ray-Tube type, in which we could control the intensity of the three primaries. Yet, on a CRT, the definition of the stimulus is three-dimensional and linearly related to cone excitations.

Then we had to render a plausible appearance of the image. Reproducing how an image appears to dichromats was challenging. Given that a dichromat confuses a given red and a given green, how would these confused colours be perceived, and how should they be represented? Should the representation be red? Or green? Or yellow?

Appearance for a protanope→



Appearance for a deuteranope→

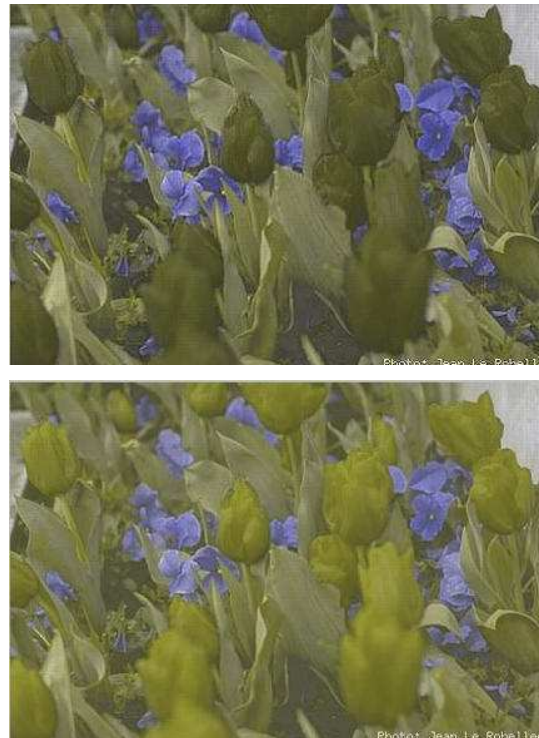


Figure 1. Simulation, for the normal eye, of the appearance of a flower bed for the dichromat (Viénot et al., 1995).

In his pioneer study, Judd had carefully reviewed the literature about unilateral colour defects which shows that for protanopic and deuteranopic observers, the colour perception of the spectrum is confined to two hues, yellow and blue. Judd's choice has been to represent, for a normal colour observer, all corresponding colours that are confused by dichromats by a unique sample of hue 5PB or hue 5Y of the Munsell Book of Colors. Precisely, Judd has given quantitative estimates of the colour perceptions typical of protanopic and deuteranopic observers for the whole range of Munsell colours. The same choice was retained by Meyer and Greenberg in a computer graphics simulation of dichromatic vision, prior to ours.

Our choice has been to maintain the normal colour appearance of white and greys and the same two hues of the stimuli at 475 nm and at 575 nm for protanopes, deuteranopes and normal trichromats. Finally, a photograph from a flower bed, at the Jardin des Plantes in Paris, has served to illustrate the simulation (Figure 1).

Now softwares have been written by many groups, some of them being available online. Figure 2 shows, for a trichromat, how the AIC 2015 logo (1st line) appears for a protanope (2nd line) and a deuteranope (3rd line).



Figure 2. Colour-blind simulation of the AIC 2015 logo.

3.2 Specificity of the luminance information (operational dimensionality)

The visual system network distinguishes between chromatic and achromatic pieces of information, the latter being prominent. Practically, the most efficient visual signals in nature which help the individual to localize targets and to move in the environment are based on luminance contrast.

Although the normal individual colour vision is trichromatic, behavioural responses to situations implicating resolution of high spatial and temporal frequencies depend principally on an achromatic mechanism with a spectral sensitivity much like $V(\lambda)$. Provided that the detection of high spatial frequencies or high temporal modulations depends on luminance contrast only, the chromaticity of the stimulus does not modify visual performance. Psychological evidence is obtained using the techniques of heterochromatic flicker photometry or minimally distinct border, among others. Thus, the high frequency spatial colour vision reduces to one dimension.

Lennie et al. (1993) recognize that the nature of underlying post-receptoral mechanisms is equivocal. Either LWS and MWS cone signals are directly summed into the magno-cellular pathway, or they are indistinctly processed so as issuing an additive signal.

3.3 The colour of illumination (contextual dimensionality)

Colour specification is well controlled by lighting engineers. With the emergence of solid-state technologies, much care is taken to correctly assess the colour of light. Indeed, for humans, the reference to qualify white light is natural daylight that needs only two variables to be qualified: the illuminance at earth level and the colour temperature.

Having measured the spectral power distribution (SPD) of real daylights, Judd and co-authors (1964) concluded, however, that distributions could be satisfactorily reconstituted by using only the first two principal components derived from principal component analysis (PCA). Later, Hernández-Andrés and colleagues (2001) concluded that more than two characteristic vectors were needed for good reconstruction. Even though they observed some departure of clear-sky colour from the CIE daylight locus, the chromaticities they measured are pretty much aligned along a unique curve.

Given the shape of the daylight locus and the dominance of the first two principal components in the analysis of daylight distribution, the question arises whether the three-dimensional colour specification that is used to specify the colour of material items is the one that should be used to scale illumination. We will see later in this paper that a specific visual channel is excited by light which might imply that the dimensions of the colour illumination world are only two.

4. EXPANDED DIMENSIONALITY COLOUR WORLDS

4.1 Additional photopigments (individual dimensionality)

Whereas the colour image domain exploits at best the three dimensions of colour, the questions arises whether the colour vision of the observer who looks at images could be more than three-dimensional.

4.1.1 Tetrachromatic mothers

Anomalous trichromats possess three cone pigment families. Nevertheless, one pigment family differs from the normal's cone pigment. Men inherit the LWS and the MWS pigment genes from their mother. The likelihood that behavioural tetrachromacy exists in carriers of anomalous trichromacy was addressed by Jordan (Jordan et al., 2010). Although most carriers of colour anomaly do not exhibit four-dimensional colour vision, Jordan and colleagues found 1 of 24 female carriers who exhibited tetrachromatic behavior on a colour matching test (Rayleigh matches). Genetic analysis showed that this mother had three well-separated cone photopigments in the longwave spectral region in addition to her short-wave cone which makes the sum of cone families equal to four. Nevertheless, it may be noted that this human observer has been just able to express trichromacy in a task where the canonical normal colour observer expresses dichromacy.

4.1.2 Fish and birds tetrachromatic vision

Fish and birds possess four families of cones. Although narrower tuning of the cone sensitivity might impair differential sensitivity, behavioural tests show that birds and fish enjoy tetrachromatic colour vision (Kelber and Osorio, 2010).

4.2 Additional receptors: rods and melanopsin (operational dimensionality)

Besides extra cone pigments, there are two photopigment families other than cone pigments, and with a different spectral sensitivity, which could be candidate to increase the dimensionality of colour vision.

4.2.1 Rod contribution

Rods, the spectral absorption of which, measured in the corneal plane, peaks at 507 nm, are active at mesopic levels.

Clarke (1973) and Trezona (1973) in early AIC conferences, demonstrated how to achieve a tetrachromatic colour match that holds at photopic and scotopic levels. To match every monochromatic radiation, they needed four primary matching stimuli of which they used one or another set of three. A unique match could be reached by iterative convergence. While the unique answer is recorded on the basis of the known colour sensations, this procedure ensures physiological identity of quantum absorption in four receptor responses.

4.2.2 Melanopsin interaction

During the past decade, it has been discovered that a few retinal ganglion cells contain a photopigment named melanopsin which can absorb photons before they reach the cone and rod layers. The melanopsin spectral sensitivity peaks at about 490 nm (estimated at the entrance of the eye), between SWS cones and rods' peak sensitivity. The so-called intrinsically photosensitive retinal ganglion cells (ipRGC) are stimulated at high mesopic and photopic illuminance levels (Dacey et al., 2005).

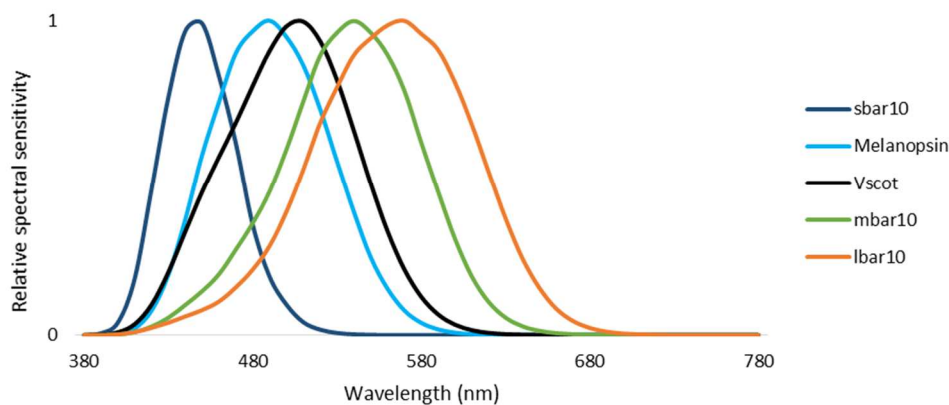


Figure 3. Cone, rod and ipRGC spectral sensitivities.

Using pharmacological tracers in the monkey brain, it has been shown that ipRGCs project to cortical and sub-cortical areas of the brain (Dacey et al., 2005; Hannibal et al., 2014). They convey information that is not principally devoted to image formation but mediate other visual functions such as the circadian rhythm and the pupillary reflex, and influence awareness and mood (Lucas et al. 2014).

The effect of the spectrum on non-image forming fonctions.

As pupil aperture is easy to record in real situations, we conducted experiments to test whether it was possible to drive the pupil response in accordance with the excitation of rods and ipRGCs (Viénot et al., 2012). Our experiments rest on the fact that metamers could differently address rods and ipRGCs. To investigate this question, at least 5 independent primaries are necessary. In a multi-LED light booth equipped with 7 types of colour LEDs, we could modulate the light spectrum, maintaining the white illumination at the same luminous level and the same CCT. Thus, the LEDs were driven so as to obtain metameric

white lights that would excite rods and ipRGCs at most or at least (Figure 4). We continuously photographed the pupil of the observers under each 7 colour LED illumination to measure the pupil diameter.

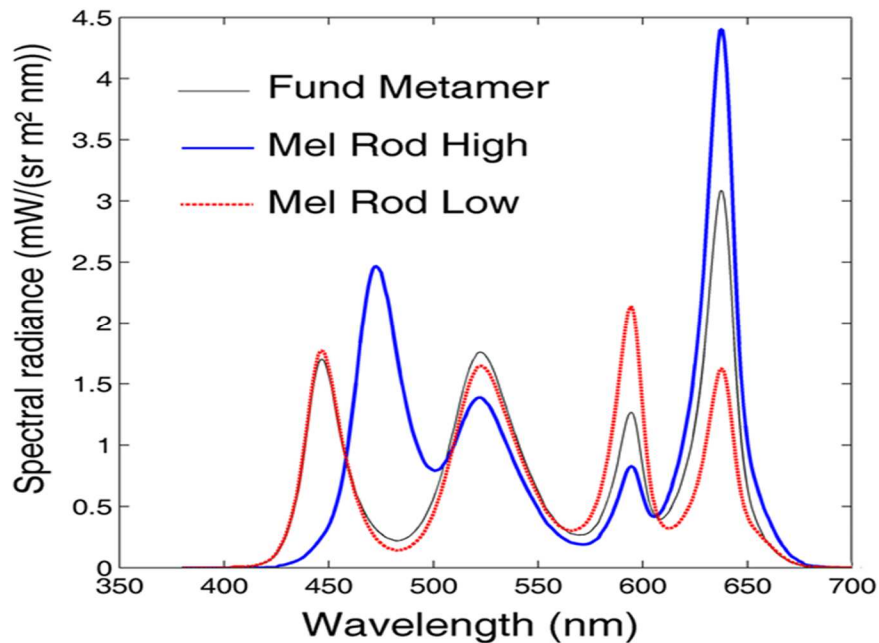


Figure 4. Two metameric white lights that would excite rods and ipRGCs at most or at least (Viénot et al., 2012).

Indeed, we verified that, with metameric white lights that generate identical signals in cones, the pupil diameter varies depending upon the spectral content of the light, which indicates that the light spectrum has an effect on visual functions, besides consciously seeing colours.

For domestic lighting, we draw attention to the possibility that driving the pupil reflex and possibly other non-image forming visual functions using unnatural spectrum would generate an uncomfortable behaviour.

Whether melatonin interacts with cone colour vision is still unsolved. Brown et al. (2012) have hypothesized that ipRGCs may contribute to distinguishing brightness. Horiguchi et al. (2013) collected detection (difference) thresholds to many stimuli, using four-primary stimuli. Trichromatic theory explains foveal sensitivity, with no need to invoke a fourth photopigment. At high photopic levels where rods are not active, a fourth photopigment is required to explain peripheral sensitivity.

4.3 Four pigments and colour constancy (operational dimensionality)

Colour constancy is a visual phenomenon which we encounter every day. The perceived colours of reflecting surfaces remain satisfactorily stable despite changes in the spectrum of the illuminating light.

Where discounting for the illuminant change originates from is not understood yet. Simple models rely on the von Kries coefficient laws and state that the global change of illumination can be extracted from proportional changes of the cone excitations triggered by the reflecting surfaces in the scene. The gain change could operate within the retina.

However modern scientists question the complexity of colour constancy. They argue that the visual system makes a distinction between the estimation of the illuminant and the changes of surface reflectances.

Foster and colleagues (Craven and Foster, 1992; Foster, 2011) settle experiments where they introduced changes in illuminant colour and/or changes of material colour properties. They showed that subjects had been capable of correctly discriminating the two situations. They concluded that the visual system is provided with information about a changing world in “advance of the generation of a more elaborate and stable perceptual representation”.

Hyperspectral images of natural scenes have revealed the occurrence of metamers in nature which indirectly means that the natural world is higher dimensional than the CIE colorimetry world (Foster et al., 2006). Of interest is the recent analysis of Barrionuevo and Cao (2014) who showed that the natural object spectra are not only discriminable by cones but that part of the spectral information can be decoded by melanopsin. Principal component analyses conducted on the excitations of rhodopsin, cone opsins, and melanopsin for natural hyperspectral images revealed that the sum of all responses (“L M S R I”, with “I” for ipRGC) may contribute to the magno-cellular pathway and respond to irradiance levels. The PCA further suggests that rod and ipRGC signals also may contribute to post-receptoral pathway components that oppose LWS and MWS cone, with various combinations.

The putative role of a fourth photopigment to disambiguate the colour material factor from the colour illumination factor has been addressed in the context of colour constancy. In the future, investigation of the role of melanopsin signals might bring renewed knowledge about colour constancy as well as to the concept of colour temperature.

4.4 The generalized metameric approach. Metamers in the four- or five-dimensional framework

In the context of the three cones space, metameric colour stimuli have different spectral power distributions, but they excite the three families of cones similarly.

Investigation of the metamer domain has been facilitated using the concept of “metameric blacks” introduced by Gunter Wyszecki in 1953. (A simple example might be: given two real metameric stimuli, a metameric black is obtained by subtracting the SPD of one stimulus from the other.) Wyszecki presented the view that the spectral power distribution of metamers consists of two component spectral distributions: the fundamental distribution, named “fundamental metamer”, that controls the three cone responses (and consequently the colour specification of the stimulus) and a secondary distribution that has no effect on cones, which he named a “metameric black”. Cohen and Kappauf, in 1982, presented a procedure for accomplishing the decomposition of any visual stimulus into the fundamental metamer and the black component.

Adding a metameric black to a fundamental metamer has no effect on cone responses. However adding a metameric black to the fundamental metamer may well modify the responses of the rods and of the melanopsin cells. In order to investigate the domain of metamers in a space of higher dimensionality than the cone fundamentals’, it is possible to extend Cohen and Kappauf’s procedure for producing SPDs that excite or do not excite identified photoreceptors. Let us note that two metamers for a dichromat may not be metameric for the trichromat, two metamers for a trichromat may not be metameric for a four receptor visual system, two metamers for a four receptor system may not be metameric for a five receptor system, etc

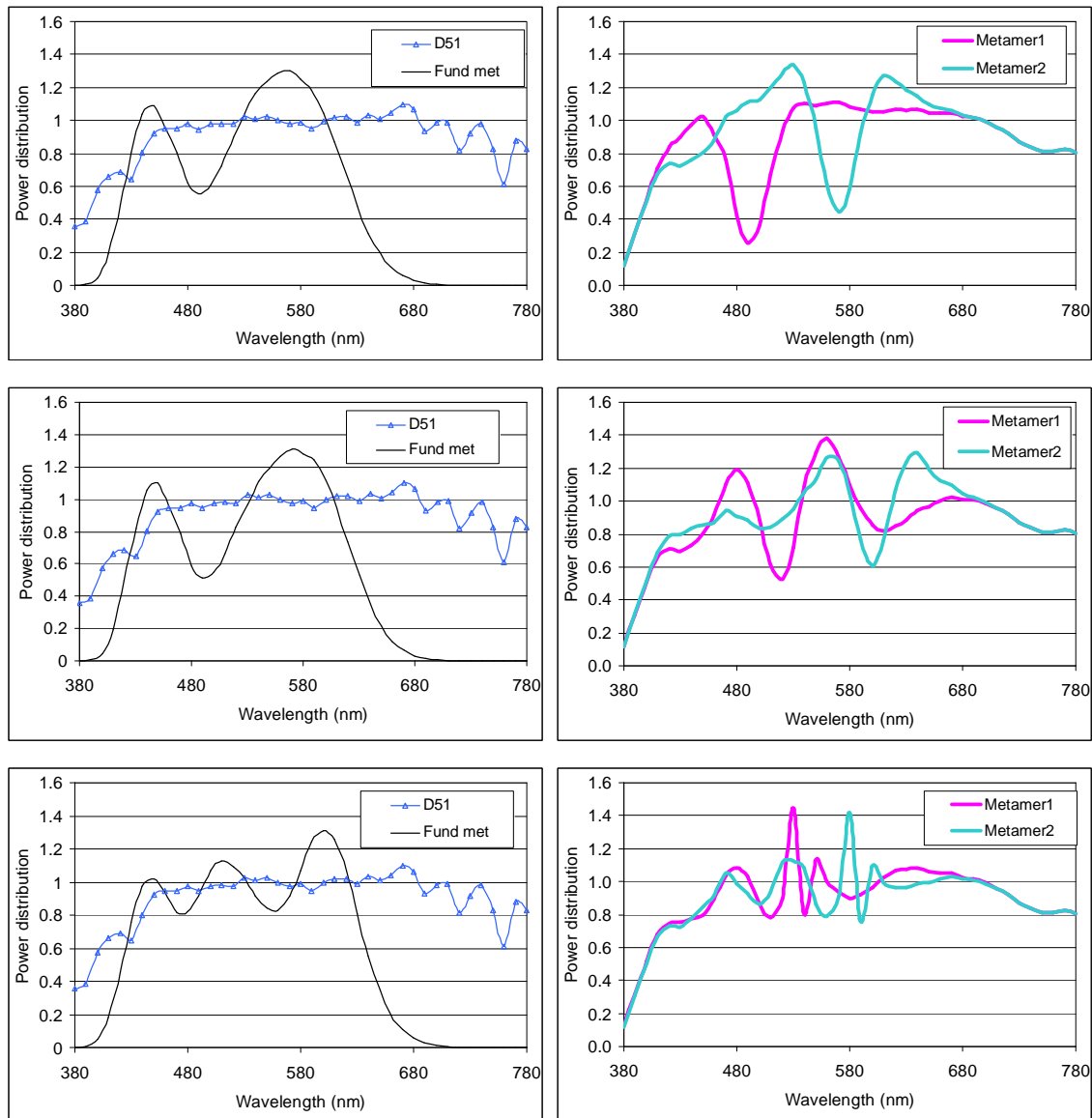


Figure 5. Metamers of daylight at 5100 K

Figure 5 shows examples of metamers of daylight at 5100 K for a variety of dimensionality of the visual receptor system. On the first line, the graphs show metamers for the deuteranope who lacks MWS photopigment. On the second line, the graphs show metamers for the normal trichromat. On the third line, the graphs show metamers that match for the three cone types as well as for rods and melanopsin cells. The left column presents the SPD of natural daylight at 5100 K and its fundamental metamer. In a previous paper, we already mentioned that, in the three-dimensional colour space, the fundamental metamer distribution resembles the SPD of modern light-emitting diodes. Thus while LED lighting mimics the colour of natural light it does not suit rod and melanopsin cells natural excitation. The right column presents two arbitrary chosen metamers with markedly different spectral power distribution. It can be seen that, as the dimensionality of the receptor system increases, the number of crossings of the two metameric stimulus functions increases. Note also that Metamer 1 and

Metamer 2 designed for the deuteranope would appear reddish and greenish to a colour normal observer.

4.5 The necessity of categorisation (contextual dimensionality)

Whereas receptor-level colour coding ensures continuous capture of the available information about the environment, we tend to group into categories the colour we perceive.

It is not clear whether categorization can be included in a dimensionality framework, for dividing the information into a small number of well-defined regions of the colour space tears the continuous dimensions of colour and introduces irregularities in the colour space (Jameson, 2005). Further, language, as a normative process of colour space segmentation, influences the way colour samples are grouped based on their perceptual similarities (Bonnardel, 2013).

What is accepted is that color categorization helps us to reliably and quickly identify objects and materials within a scene. It is an essential perceptual phenomenon.

CONCLUSION

On the one hand, stating that colour vision is three-dimensional strictly applies to the cone fundamental space. It has helped the CIE to found standard colorimetry and recently to revisit the cone fundamental space (CIE, 2006).

On the other hand, the dimensionality of colour vision may vary depending on the individual, the task and the context. It is a challenge for the future to establish relationships between one or another colour space and to find the best way to define the colour of the world.

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