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Perception

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Abstract. The following chapter introduces the readers to the complexity of colour perception, emphasizing that colour is not an intrinsic property of objects, but a perceptual quality derived from the interaction between light and HVS, the human visual system. It analyses how light, interacting with material surfaces, influences perception through reflection, transmission, and diffusion. The chapter describes the trichromatic theory, which explains that three types of retinal cones (sensitive to short, medium, and long wavelengths) allow the perception of a wide range of colours. Phenomena like metamerism, where different colours appear similar under specific lighting, are also considered, as well as review Hering's opponent-process theory. Finally, the authors discuss the role of chromatic induction where adjacent colours influence the perception of a given colour, demonstrating how colour perception is a dynamic and contextual process.

Keywords: Perception · Colour Vision Deficiency · Multisensory

1 Colour Perception in Human Vision

The Basics of Colour Perception. Most naturally luminous or illuminated objects have the property of being coloured. This self-evident property of objects is not so obvious at first. The objects around us appear red, green, yellow or multicoloured, not because they are so per se, but because that is how we 'see' them. Colour is not an intrinsic physical property of objects, but rather a psychological property that characterises our visual perception i.e. it is a perceptual quality. The colour that we perceive is clearly due to the physical properties of objects, and it is because of these properties that we see objects in colour. However, colour is essentially different from these properties, and arises because of complex interactions between the light with our visual nervous system in the surrounding space or context. Colour can be derived from a variety of physical, chemical, and biological mechanisms [1]. But there are also cases where we

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have transient colour illusions, that is, we perceive colours that do not result from an external light stimulus but are caused by physiological causes, due to normal reactions of the visual neurons when stimulated by other factors.

Colour and the Interaction of Light with Material Surfaces. When light interacts with a surface, the physical effect (reflected light) is described as a spectral emission distribution resulting from the product of the spectral power distribution curve of the light and the spectral reflectance of the surface. The characteristic absorbance of a material, due to its molecular or crystalline structure, is the most common cause of colour. Colours of natural dyes and inorganic pigments from minerals (e.g. azurite or lapis lazuli), colours of precious stones (e.g. amethyst) and a plethora of rocks in nature or colours of synthetic pigments (e.g. ultramarine), belong to this category. Colour vision, an aspect of visual perception, is the ability of the human visual system (HVS) to perceive differences between visible light with different spectral characteristics. This luminous stimulus is perceived as colour, which our visual system does not analyse spectrally, but "translates" it, in terms of its three independent psychological dimensions: hue, saturation, and brightness.

The perception of colour as a result of the interaction of light with material surfaces, presupposes, and depends on three elements:

1. light and its spectral power distribution.
2. the physical properties of the surfaces which reflect or transmit or diffuse part of the light, depending on the composition of their matter and the microstructure of their surface; and
3. the functions of the observer's visual system, which is capable of distinguishing the spectrally modulated light that is re-emitted from the surface of objects.

However, colour perception is a more complex process that involves the reception of light by photoreceptor cells, the processing of colour information in the visual system, from the retina through the optic nerve to the primary visual cortex (V1) and higher visual areas in the brain, where interpretation of colours is influenced by both physiological and cognitive factors. Before modern neuroscience opened new avenues for understanding the mechanisms of colour perception, psychophysical experiments played a crucial role in the conceptualisation, testing, validation and evolution of colour theories and colorimetry. Psychophysical experiments were and still are the most important tool for the experimental study of visual perception and the mechanisms of colour vision by investigating the psychological response to physical stimuli, i.e. the relationship between perception and external colour stimuli. The psychological dimensions of colour, as perceived by the visual system of an observer with 'normal' colour vision, correspond to the physical dimensions of the light stimulus resulting from the interaction of light with the surface. But how are the psychological and physical dimensions of colour related?

Hue vs Dominant Wavelength. Hue is defined in the CIECAM02 model as "the degree to which a stimulus can be described as similar to or different from stimuli that are described as red, orange, yellow, green, blue, violet" [2]. The hue of a colour is what allows us to differentiate between different colours, without considering their brightness or saturation. On the other hand, dominant wavelength is a method used to describe a colour's hue in terms of its spectral composition. A colour's dominant wavelength

is the wavelength of monochromatic light which appears most similar to the colour in question. While hue is a perceptual attribute categorising colours into distinct groups, dominant wavelength is a physical measure describing the wavelength of light most influential in determining the perceived colour. In some cases, the hue and dominant wavelength of a colour may match closely. However, in most cases, colours perceived as the same hue may have different dominant wavelengths due to differences in spectral composition. Newton's discovery that "white" light is complex and consists of a few distinct components that are perceived by the eye as autonomously different colours is undoubtedly a milestone in our understanding of the nature and perception of colour. In the 17th century, Newton demonstrated that when a narrow beam of sunlight passed through a prism, the white light was dispersed into a spectrum. When one of the coloured beams was passed through a second prism, the identical colour persisted, proving these beams are unique and can be used to define colour. These are known as spectral colours, as they are produced by a single wavelength. The visible spectrum ranges from 380 to 780 nm.

Saturation vs Purity of a Chromatic Stimulus. The second perceptual attribute used to describe colour is saturation. Saturation refers to the vividness of a colour relative to its brightness. Normally, this is described as the distance of the colour from a neutral grey of the same brightness level. A fully saturated colour is considered pure and appears vivid and intense, and a fully desaturated colour becomes achromatic. Desaturated colours contain a mixture of the pure colour with white light and appear muted. Purity, also known as chroma or colourfulness, is the dominance of a particular hue in a colour stimulus. It is commonly assessed in comparison to a fully saturated colour of the same hue. For example, a colour with high purity contains the specific wavelength or mixture of wavelengths associated with its hue, and a colour with lower purity will also contain wavelengths associated with other hues.

Value or Brightness vs Integral of the Reflectance Over the Entire Visible Spectrum. The third perceptual attribute that describes colour is value or brightness. It describes how bright or how dark an object appears to an observer, regardless of its hue or saturation. The integral of the reflectance over the entire visible spectrum is the mathematical calculation that gives the total amount of light reflected by an object across the entire visible spectrum. These two concepts are related as the brightness of an object depends on the total amount of light it reflects, but it is not solely determined by it. The perception of brightness also involves factors such as the spectral power distribution of the light, and higher order mechanisms such as the contrast between the object and its background. The HVS perceives the brightness of an object by comparing it with that of a perfectly white object. This quantity is defined as lightness and refers to the colours of objects rather than to light sources, and ranges in the grey scale. The lightness of a reflective surface depends on the percentage of light energy reflected from the surface, but the relationship between lightness and light energy is not linear, but logarithmic, so equal steps in reflectance are perceived as smaller changes in lightness at higher levels of brightness.

Colour Vision and the Trichromatic Theory. The mechanisms involved in human colour perception are both physiological and psychological [3, 4]. The HVS is responsible for this (Fig. 1). When light enters the eye, it is focused on the retina. The photoreceptor layer at the back of the retina is made up of a combination of photosensitive receptors called rods and cones. Cones are mostly concentrated in the central area of the retina, the macula, which contains the fovea. The central fovea contains 100% cones. Cones support the brain process known as photopic vision, which involves colour vision at varying levels of illumination. Humans have three types of cones which have different spectral sensitivity [5], sensitive to short (S), medium (M), and long (L) wavelengths, resulting in trichromatic colour vision [6]. The three types of cone cells (S, M, and L) do not transmit information about the spectral composition of light. However, the wavelength of light determines the probability that a cone will be excited (i.e. absorb photons); and thus, transmit an electrical signal to the ganglia to which it is connected. The spectral sensitivity curves of the cones of the human eye, as defined by the International Commission on Illumination (CIE), based on experimental measurements of a set of observers with normal vision, express precisely the probability that cones are excited by light as a function of wavelength. If we simulate the photosensitive subretinal leaflet of the retina with a detector whose photosensitive surface consists of a mosaic of unit detectors R, G and B in different ratios, then the three colour simulation curves combined correspond to the total spectral sensitivity of the detector system [7].

According to the trichromatic theory, first proposed around 1801 by Thomas Young, an English physician, and refined about 50 years later by the German scientist Hermann von Helmholtz, the human visual system perceives colour as a triad of stimulus values (which can be represented in a three-dimensional colour space comprising the set of perceived colours). The tristimulus values correspond to the degree to which the three types of cone photoreceptors, sensitive to short (S), medium (M), and long (L) wavelengths respectively, are stimulated [8].

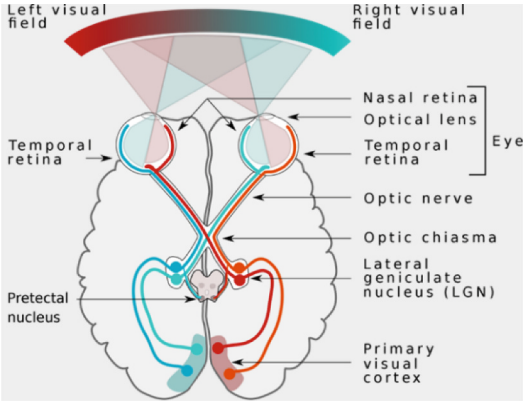

Fig. 1. The human visual system (from Wikimedia Commons, Miquel Perello Nieto)

Although the HVS is defined as trichromatic, its capacity to recognise and differentiate different colours is very extensive. It has been shown that an individual with standard

vision can distinguish two hues of around 5 nm spectral difference, and it can achieve a performance peak of around 2 nm at two areas of the chromatic space, specifically in the yellow and blue-green regions [9]. While the perception of colour by the HVS can be very sensitive, it is limited by the encoding of a whole continuous spectrum into three coordinates.

The fact that the mixture of only three primary colours is sufficient to simulate all perceived colours is explained by the ability of the visual system to perceive a multitude of colours, attributing to each distinct colour a unique combination of stimulation of the three types of cones in the retina. The trichromatic theory explains the three most common cases of colour vision deficiency (dyschromatopsia or partial colour blindness) attributed to the absence of one of the three types of cones from the retina. The tri-retinal determination of the colour of a target object is obtained by weighting the spectral power distribution of the light reflected from the object by the three spectral sensitivity curves (colour matching functions) corresponding to each type of cone. This principle was the foundation of modern colorimetry, whose basic principles, laws, and data are derived from psychophysical experiments.

A prerequisite for the validity of psychophysical experimental results is a clear definition and the ability to isolate the physical stimulus (e.g. colour) under investigation, so that only the response to the specific stimulus is measured each time. Accordingly, colorimetric measurements and representations in different colour spaces correspond to the colour as perceived by our visual system isolated from the colour environment. However, the perception of colour in a colour composition or a scene, in a natural space or in a designed environment does not occur in isolation, but as a whole. Colour perception activates all the physiological mechanisms of the visual system: colour induction, colour adaptation and colour constancy.

The trichromatic theory also explains the optical phenomenon of metamerism. Illuminant metamerism occurs when two surfaces of different materials; and therefore, of different spectral reflectance, appear chromatically similar under one light source and chromatically divergent under another light source with a different spectral power distribution. Observer metamerism, occurs when the same material, under the same illumination is perceived as having a different colour by two different observers. The recognition of the colours of a metameric pair is explained by the fact that two colours can have the same trichromatic values for a given illumination and observer, even though they have different spectral reflectivity curves. The phenomenon of metamerism is an obvious proof that our visual system perceives colours without recognising their spectral composition or their physical cause. Pairs of metameric colours are not uncommon in our environment, but we are not always able to recognise them in our everyday experience. It has been observed that there is a great variability in the distribution of cones in the retina, even for non-deficient observers. These variations can happen between individuals, as well as within an individual, between left and right eye, and within the fovea. If the HVS considered these spatial differences, we would perceive colour differences constantly, even when looking directly at an object and then switching to peripheral vision, which is not the case. Therefore, the HVS is capable of extracting properties from objects as well as abstracting itself from variations in the distribution of cones.

The Neural System and Colour Perception. The Theory of Antagonistic Colour. Although the trichromatic theory consistently explains the trichromatic sensitivity of the photosensitive retinal sheet, it fails to explain observed phenomena in colour perception as a conscious subjective (psychological) experience resulting from the overall functioning of the visual system. Investigating the phenomenological dimension of colour perception and in contrast to the supporters of the trichromatic theory, Ewald Hering (1834–1918) developed at the end of the 19th century the opponent process theory (Fig. 2), according to which vision shows colour sensitivity to colours perceived in the following three dimensions: the green-red axis, the blue-yellow axis, and the black-white axis. About a century later, DeValois, Abramov and Jacobs confirmed Herring's theory. Studying the cells of the lateral geniculate nucleus (LGN), they distinguished six cell types. Four types that respond in an antagonistic manner: (R+ G−); or (G+ R−); (B+ Y−); or (B− Y+), and two types of non-antagonistic cells (Wh+ Bl−) or (Bl+ Wh−). The latter two types of non-antagonistic neurons contribute to the distinction of white and black and convey lightness information to the details of an image, regardless of colour. A hundred years after Hering's theory of antagonistic processes was formulated, and thanks to the contribution of other theorists, Leo Hurvich (1910–2009) and Dorothea Jameson (1920–1998) formulated the dual process theory in 1957, which came to bridge the trichromatic theory with the theory of antagonistic colours, proposing a synthesis of the two. According to the two-stage theory, in a first stage the receptors operate trichromatically, and then the output signals of the first stage are input signals of the second stage in which processing takes place based on the theory of competing mechanisms [10, 11]. The two stages of processing, according to the theoretical model of Hurvich and Jameson's theory, take place in the retina, which has been confirmed by subsequent physiological studies [12, 13]. It is widely used, since it is a reasonable simplification of colour vision [14].

Colour Perception as a Function of Lightness and Colour Contrasts. Due to the organization of the synaptic connections and the processing of the signals transmitted through them, the signals emitted by each photoreceptor contain simple light intensity information in the spectral region to which it is sensitive. On the contrary, signals emanating from the ganglia and transmitted through the LGNs contain light intensity difference (contrast) information. This is further processed in subsequent centres of the visual cortex (V1, V2, V4), by so called dual antagonist cells. These neurons respond simultaneously to both spatially competitive signals, between the centre and periphery of their receptive field, and to chromatically competitive signals (bipolar response R+G− or G+R− or R+G− or G+R− or B+Y− or Y+B−). These cells are selective to colour contrasts between neighbouring regions contributing to the perception of the individual elements of the visual scene. In summary, the function of the cone photoreceptors verifies the trichromatic theory, while the function of the ganglion cells and LGN cells, process the signals of the photoreceptors falling within their receptive field, in accordance with the theory of the antagonistic process. Therefore, colour is first determined by the response of the three types of cones and then recoded by the ganglia into a colour contrast signal. The connections of neurons in the primary visual cortex are such (their subfields have an appropriate spatial organization) that the colour coding is of dual antagonism, both

chromatic and spatial. Thus, colour is coded not as the absolute colour of a point but as a colour contrast between adjacent areas.

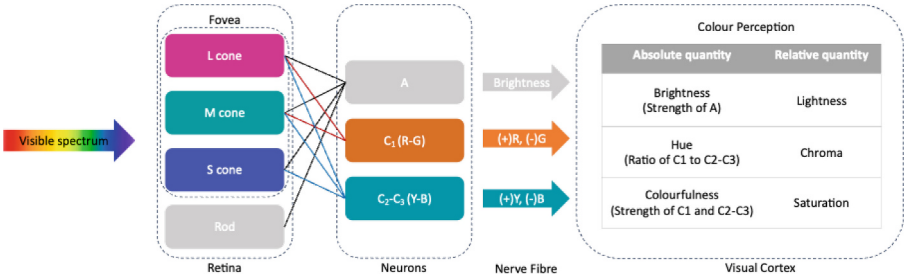

Fig. 2. Opponent process theory

If we relate the physiological functions of visual perception to artistic creation, we could say that a painter does not copy nature, but rather perceives it in terms of relationships/contrasts of lightness and colour, so that they can then capture the 'feeling' they get in their work. Since what we see is determined both by the laws and organisation of the brain, and by the tangible reality of the outside world; art, from another perspective, is a special kind of investigation into the laws governing perception and the aesthetic fulfilment we derive through perception [15].

Chromatic Induction – Interaction of Adjacent Colours. The perception of the colour of a stimulus is predictable based on its spectral composition, under certain conditions of observation and illumination, with the basic assumption that the stimulus is observed in isolation from other colour stimuli. However, in the case of observing a complex chromatic sequence or scene, the perceived hue of a stimulus may change drastically under the influence of other colours in the visual field, especially those immediately adjacent. The change in apparent colour that occurs when an object is observed in the presence of other coloured objects is called chromatic induction. Chromatic induction is a general term that includes individual discrete phenomena such as simultaneous contrast and chromatic adaptation [16]. Chromatic induction is observed not only in the case of strong hue contrasts between adjacent colours, but also in the case of strong contrasts in lightness between adjacent colours. The effect of chromatic induction can be quite significant. For example, in the case of 'simultaneous contrast' the observed colour objects have lightness and hue close to those of their complementary surroundings (Fig. 3). Then, the possible difference in perceived hue tends towards the complementary colour of that which is interacting and causing the chromatic induction. Also, we can say that when perceiving a visual-colour target surrounded by a uniform background, the chromatic components (chromaticity and luminance), which are common to the central colour and the background, do not contribute to the perceived colour of the visual target. That is, the perceived colour results from subtracting the background colour from the observed target colour.

The phenomenon of chromatic induction was known to artists and scientists in the 19th century, with Michel Eugène Chevreul (1786–1889) and Helmholtz being the most

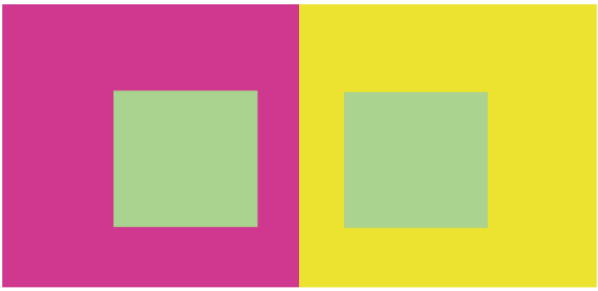

Fig. 3. Simultaneous contrast of colour: when a colour is surrounded by a neighbouring colour, the perception of its colour shifts to its opposite neighbouring colour. Left: An olive green square surrounded by magenta background, shifts in visual perception towards brighter green. Right: An olive green square surrounded by yellow, shifts in visual perception towards darker green (bluer). (Color figure online)

important theoretical representatives. In the 20th century, the most important study of the phenomena of chromatic induction and their application in painting was proposed by Josef Albers (1888–1976) at the Bauhaus School [17]. The interaction or enhanced contrast between adjacent colours is perceived and interpreted by the law of chromatic competition and simultaneous contrast. When colours of a competitive relationship (red-green, blue-yellow) coincide spatially, they cancel each other out (chromatic antagonistic effect), while when they are adjacent to each other they enhance each other (simultaneous contrast effect). Another artist who explores chromatic induction is Carlos Cruz-Diez. In his works *induction chromatique*, he explores complementary colour due to retinal persistence. Cruz-Diez shows that the colour induced on our retina is as real as the colour painted on the surface of an object. Thus, colour is a sensation on the brain of the viewer. Another process which happens along the visual pathway is that of **signal compression**. Considering light aimed at an eye increases in even increments, the resulting visual signal will increase but in diminishing increments. This has been illustrated by Joseph Albers 1963, plate xx-1. For a visually uniform increment, cube-root increments of black should be used [18].

Colour Constancy. Perhaps the most important attribute of colour perception is colour constancy: the fact that the colour of surfaces remains largely unchanged despite any -considerable- variations in the spectral composition of light. Both retinal and cortical factors contribute to colour constancy. Cells in the primary visual cortex (V1) with both spatial and chromatic opponency ('double-opponent' cells) might be important in colour adaptation which significantly supports colour constancy [3].

The 'strategy' used by the brain to ensure colour constancy is not precisely known, but several alternative explanations of the phenomenon have been proposed. Most interpretations converge on the conclusion that we are able to distinguish and identify colour under large variations in the light source thanks to the fact that our visual system responds to colour differences/contrasts rather than to individual colours. In other words, the brain encodes colour as a combination of chromatic and luminance contrast relative to the surrounding environment of the target surface (colour induction mechanism). Thus, given the mechanism of colour perception in relation to its competing environment, the colour

we perceive remains constant and independent of the intensity and chromaticity of the lighting conditions. In fact, the visual system seems to be able to "subtract" from the observed colours the intensity and chromaticity of the general illumination, so that it perceives colour as the exclusive result of the reflectance of the surface of objects. It has been argued that chromatic induction can be seen as a consequence of the generalised application of the mechanism of colour constancy. For the perception of the scene, vision is assisted by colour adaptation, so the colour of the background becomes perceived as the prevailing illumination hue and is subtracted from the target colours [18].

Chromatic Adaptation. While the perception of colour can be generalised to standard observers, we have experienced that we do not always see the same colours. An example of this is the viral 2015 picture of #theDress [19–21] (Fig. 4). While some of us saw the dress white and gold, others saw it blue and black. This is because the HVS is constantly inferring queues from the scene and adapting [22]. These adaptations can be spatial, based on the scene and objects in the surrounding, as well as temporal, known as ***chromatic adaptation*** [23].

Fig. 4. Original image of a dress people may see as blue/black or white/gold (Wikimedia). (Color figure online)

Chromatic adaptation refers to the ability of the human visual system to adapt to the particular lighting conditions whose spectral composition may significantly vary from absolute white - in order to maintain a 'stable' appearance of the colours of an object. In other words, chromatic adaptation is the ability of the human visual system to compensate the colour of the illumination to consistently perceive the colour appearance of an object. For example, we can still perceive a white sheet of paper as white, under different light sources of different spectral composition and colour temperature. Chromatic adaptation relies on the ability of receptors to 'adapt' - that is to become less responsive - to continuous stimuli of the same wavelength of light. Chromatic adaptation occurs due to the adjustment of the sensitivity of the three types of cone cells working independently in each colour channel.

One of the first mathematical models of chromatic adaptation was proposed by Johannes von Kries (1902), who considered that the regulation of the sensitivity of the three types of cones is independent and linear in each channel. Other mathematical models and studies followed, which converge on some common empirical observations [24]. Firstly, chromatic adaptation is more complete at higher light intensity. Secondly, the light of most light sources, when operated at very high intensity, can be perceived as white. However, chromatic does not work well in the case of light sources of intense chromaticity, such as monochromatic LED sources. Finally, the adaptation ability of blue cones is comparatively lower.

Successive Contrast and Afterimages. Successive contrast occurs when the perception of currently viewed stimuli is modulated by the effect of previously viewed stimuli. The colour afterimages that are observed after the eye has been exposed to coloured light for a period of time can be explained in terms of changes in the relative adaptation of the three types of cones. After a period of exposure to coloured light, the cone type that is relatively weakly stimulated by this light, due to the lack of certain wavelengths, adapts proportionally to darkness. When neutral light is restored, a temporary illusion of a light composed of the 'missing' wavelengths is observed. The colour of an afterimage affects the apparent colour of objects observed after the stimulus in the same field of view, a phenomenon known as successive contrast.

Colour Perception and Cognitive Factors. Moreover, colour perception can be influenced by categorical factors. For example, the study by Berlin and Kay [25] studied how colours would be categorised if there were only 2, 3, 4, and 5 colour terms. Berlin and Kay, also assert that languages can be constrained to up to 11 basic colour terms. More recent studies, have shown that for the English language, these can be augmented to 13 colour terms [26]. It has been shown that it is easier to distinguish two pairs of colours with a 10 nm difference which are at the border between categorical hues, for example blue and purple, than within a hue. However, most recent studies have found this debatable due to methodological reasons [27]. Furthermore, some studies support the Sapir-Whorf hypothesis that our perception of the world depends on language. For instance, research has shown that Russian speakers are faster at discriminating shades of blue for which they have distinct blue terms than non-Russian speakers [28]. This has also been tested in colour naming experiments where two "Russian blues" were used as basic colour terms, showing a significant deviation from English blue [29].

2 Colour Vision Deficiency

The human visual system (HVS) of an individual with normal vision can discern millions of colours under specific viewing conditions. Photoreceptors called cones on the retina of the eye contain pigments that respond to light of varying wavelengths: S-cones for short wavelengths, M-cones for medium wavelengths, and L-cones for long wavelengths, collectively known as trichromacy.

Colour vision deficiency (CVD), commonly known as colour blindness, refers to a condition where individuals have a diminished ability to perceive or distinguish between different colours under normal lighting conditions. It's important to note that CVD

is not a form of total blindness; rather, it affects the perception of specific colours [30]. The most prevalent cause of CVD is a defect in the development of the retinal cones responsible for perceiving colour in light and transmitting this information to the optic nerve. These cones, found in the retina of the eye, play a crucial role in the perception of colour. One significant aspect of CVD is its association with sex-linked inheritance. The genes responsible for producing photopigments, which are essential for nor- mal colour vision, are carried on the X chromosome. Therefore, individuals with missing or damaged genes on the X chromosome may experience colour deficiency. Males, who have only one X chromosome, are more likely to express this deficiency compared to females. Statistics indicate that approximately 8% of men and 0.5% of women of Northern European origin are affected by the common form of red-green colour blindness, making it one of the most prevalent types of CVD in the population [31]. Understanding the mechanisms and prevalence of CVD is essential for effective diagnosis, management, and accommodation of individuals with this condition in various aspects of life, including education, employment, and daily activities.

X-linked Recessive Inheritance. Impaired colour vision can arise from two main factors. Firstly, it can be acquired through diseases or medications, such as Plaquenil, used in the treatment of malaria, arthritis, and skin conditions, which can lead to colour blindness. However, the most common cause of impaired colour vision is an inherited defect in the development of the three sets of colour-sensing cones in the eyes. These defects often run in families and follow a specific inheritance pattern. Typically, they occur in every other generation and affect males exclusively. This is because the gene responsible for colour vision deficiency is located on the X chromosome, and males have only one X chromosome (XY), inherited from their mothers. Females, with two X chromosomes (XX), are usually carriers of the defective gene but may not exhibit symptoms of colour deficiency unless the defective gene is present on both X chromosomes. Now, let's consider a family tree: Girls inherit one X chromosome from each parent (mother and father). Boys inherit one X chromosome from the mother and one Y chromosome from the father. If the mother carries the defective gene on one of her X chromosomes, there is a chance she may pass it on to her son, resulting in impaired colour vision. In summary, impaired colour vision in males is primarily due to inheritance from the mother (Fig. 5).

Type of Colour Vision Deficiency (CVD). There are several types of colour vision deficiency (CVD) characterized by varying degrees of impairment in the perception of colours. These types are classified based on the extent of colour perception reduction, ranging from slight to complete absence. Individuals with CVD experience either a slight shift in the sensitivity of cone pigments compared to those with normal vision (known as anomalous trichromacy), or they may have certain cone pigments missing altogether (referred to as dichromacy) [32]. Monochromacy represents total colour blindness, where two or all three cone types responsible for colour vision are absent. Dichromacy denotes partial colour blindness resulting from the absence of one cone type. Anomalous trichromacy refers to a form of moderate colour blindness where all photoreceptors are present, but one type of cone exhibits a shifted sensitivity. In protanomaly, this shift occurs in the L cones, in deuteranomaly it's in the M cones, and in tritanomaly it's in the S cones. Specifically, in protanomalous individuals, the sensitivity function of L cones is shifted closer to

that of normal M cones, while in deuteranomaly and tritanomaly, the sensitivity functions are shifted towards longer wavelengths [33] (Fig. 6) Tritanopia/Tritanomaly involves the absence or malfunctioning of the S-cone (blue), Deuteranopia/Deuteranomaly affects the M-cone (green), and Protanopia/ Protanomaly impacts the L-cone (red). Anomaly, in this context, refers to a deviation from the usual rule, type, arrangement, or pattern [31].

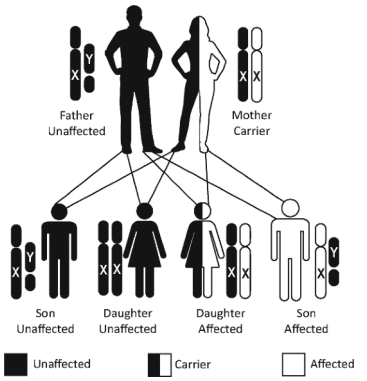

Fig. 5. X-linked recessive inheritance[1].

Confusion Lines. Confusion lines, also known as dichromatic isochromatic lines, are directional lines on a colour chart such as the 1931 xy chromaticity diagram where points lying on them are perceived as the same colour by individuals with a specific type of dichromacy [34]. For instance, protanopes, or those who are "red-blind", have confusion lines associated with them, indicating colours that cannot be distinguished by these individuals, Fig. 7. The confusion lines link a singular point (the copunctal point) with a spectral colour, indicating that colours along these lines would appear identical to a colour vision deficient observer.

Similarly, deuteranopes, or those who are green-blind, exhibit similar con- fusion lines, particularly showing difficulty in distinguishing between red and green colours, hence the term "red-green colour blindness".

While the confusion lines for both types of colour blindness are comparable, there are slight differences between them, with the intersection point often extending beyond the visible colour range, see Fig. 8. This observation underscores the shared challenges in distinguishing certain colours among individuals with red-green colour blindness, while also highlighting nuanced differences in their perception.

Human Colour Vision Test Methods. Colour vision deficiency tests aim to assess the colour discrimination abilities of individuals and determine the type and extent of any colour vision impairment they may have. Dr. Shinobu Ishihara introduced the first test on this subject a century ago, leading to the development of numerous assessments for evaluating colour perception over time. Despite considerable progress in science and

[1] https://commons.wikimedia.org/wiki/file: X − linkedrecessive.svg, accessed April 2024.

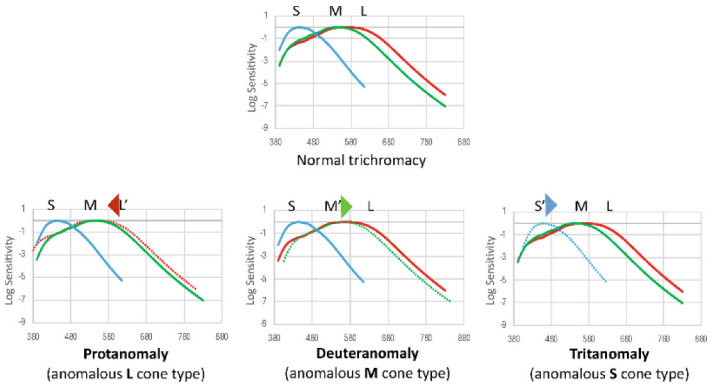

Fig. 6. Anomalous trichromacy refers to moderate colour blindness where all photoreceptors are present, but one cone type exhibits shifted sensitivity, after [33].

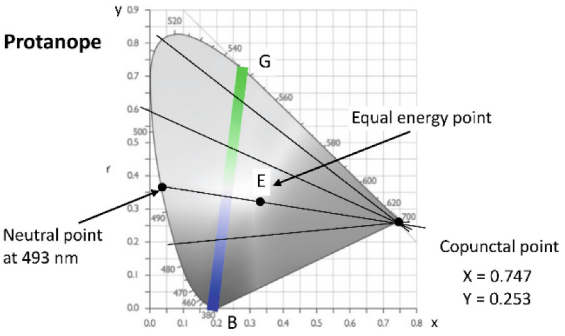

Fig. 7. 1931 xy chromaticity diagram and confusion lines for Protanope.

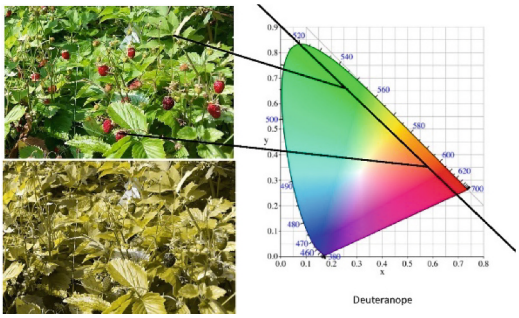

Fig. 8. Schematic illustration demonstrating the concept of confusion for a deuteranope. Both the red berries and the green leaves lie along the same confusion line. (Color figure online)

technology, the Ishihara test continues to be the predominant choice in clinical settings. However, none of the available tests provide a complete evaluation of colour vision.

There are four primary types of colour vision deficiency tests, which include:

- Pseudoisochromatic plates (recognition test)
- Ordering test (arrangement test)
- Anomaloscope
- Lantern tests

While tests utilizing pseudoisochromatic plates like the **Ishihara** [34] test claim to reliably discern between various types of colour defects, inconsistencies in their construction and printing limit their effectiveness to initial screenings only.

In 1954, **Hardy**, **Rand**, and **Rittler** (HRR) [35] introduced a set of pseudoisochromatic plates featuring different symbols such as crosses, triangles, and circles, aimed at identifying different types and severities of CVDs. A revised version of this test, known as the Hardy-Rand-Rittler test (HRR), was later developed. The HRR consists of 24 plates with coloured symbols against a grey background. By adjusting the hue and contrast of the confusion colours in the Fig from strong to weak, it becomes possible not only to differentiate between different types of CVD (protan, deutan, or tritan) but also to assess the severity of the deficiency.

The **Farnsworth-Munsell 100 Hue** [36] colour vision test is a standard assessment tool belonging to the category of hue discrimination tests, also known as arrangement tests. Its primary objective is to evaluate hue discrimination within a constant lightness and chroma curve. This test serves to identify areas of colour confusion and measure colour discrimination ability, applicable to individuals with both normal and impaired colour vision. Typically, the Farnsworth-Munsell 100 Hue Colour Vision Test consists of four rows featuring similar colour hues, each row comprising 25 distinct variations of the hue being assessed.

The **Farnsworth D-15** [37] colour vision test is effective in identifying dichromacies, particularly tritan defects. This test comprises 15 colour plates that must be arranged in the correct colour-coded order, representing a continuum of gradually changing hues. On the other hand, the **Lanthony desaturated D-15** [38] colour vision test also consists of 15 colour discs arranged to form a continuum of gradually changing hues. Like the Farnsworth D-15, the colours in the Lanthony desaturated D-15 test are less saturated. Consequently, this test is more challenging and can detect more subtle colour vision deficiencies. For accurate results, it is essential to conduct both recognition and arrangement colour vision tests in a viewing booth that replicates natural daylight conditions.

An **anomaloscope** [39] uses two types of coloured lights to test colour vision. One light is a single spectral colour, and the other light is a mix of two spectral colours. The person being tested adjusts the brightness of the single colour and the proportion of the two colours in the mix until they appear the same. This helps determine the type and severity of any colour vision deficiency.

Lantern tests [40] are the oldest and simplest confrontation colour test, initially used by the Great North Railway Company in England in 1853 and adopted as a standard colour vision test in France in 1858. An overview of multiple colour vision tests is provided in [41, 42]. Colour deficiency tests typically utilise isolated colours without including edges or altering the spatial arrangement of colours. This methodology ensures that the test focuses solely on assessing pure colour discrimination, minimizing the potential influence of extraneous factors or artifacts. Eschbach et al. [43] suggested that how well colour-deficient individuals perform on colour vision tasks depends on the

amount and structure of edge information. Later, Eschbach and Nussbaum suggested adding colour edges to assess how pure colour perception interacts with perception when edges or nearby colours are present [44]. They aimed to maintain similarity to standard tests to avoid the complexity of natural scenes, see Fig. 9. Nowadays, screens are crucial in our lives and make it easy to test colour vision using smartphones. Studies have looked at online colour tests compared to traditional ones [45–47].

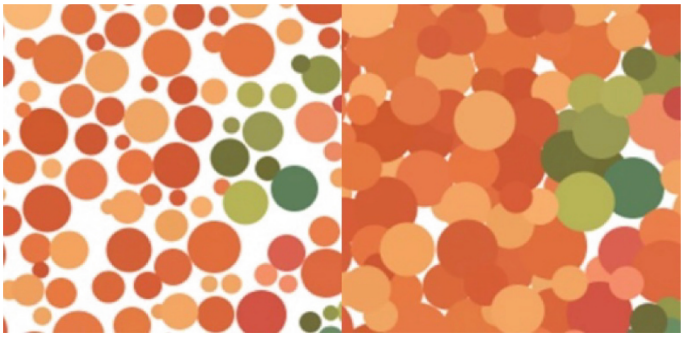

Fig. 9. Standard Ishihara chart (to the left) and a modified version (to the right) that extends the colours so that direct edges occur. This changes the overall colour appearance of the chart.

Simulation. The decrease in sensitivity along the red-green dimension results in a diminished ability to perceive certain colours, depending on the severity of the deficiency. Individuals with colour vision deficiency (CVD) encounter challenges in discerning various visual stimuli, such as navigation cues on maps and signs, interpreting colour nuances in artistic compositions, exploring historical artefacts in archaeology, and immersing themselves in digital environments. This loss of information can be approximated by predicting the ratio of cone stimulation for individuals with CVD, as highlighted in prior research [48]. However, it's important to acknowledge that while such simulations provide insights into the physiological aspects of CVD, they may not fully capture the subjective experience of colour for those with the condition [49, 50]. Green and Nussbaum demonstrated the utilization of ICC[3] profiles1 for implementing diverse transformations aimed at either simulating the visual perception of a colour image for individuals with CVD or enhancing colour discriminability for CVD observers [51].

Thus, while these simulations offer valuable tools for understanding the visual limitations of individuals with CVD, they should be interpreted with caution, recognizing the complex interplay between physiological factors and perceptual experiences.

Art and design professionals often need to check that an image or graphic will be sufficiently clear for a CVD observer, by "simulating" the effect of the colour vision loss. Simulation tools provide designers in graphic and web fields with the ability to preview their designs as they would appear to individuals with colour deficiencies, helping to identify potentially confusing colour combinations. From these simulations emerge guidelines for web accessibility, such as the Techniques for Web Content Accessibility Guidelines (WCAG 2.2)[4]. These guidelines address issues related to colour scheme selection, especially for text against coloured backgrounds across various mediums

like documents, software interfaces, and web presentations. Many simulation methods project colours from a three-dimensional colour space onto a subspace containing the previously mentioned colour stimuli along the confusion lines, Fig. 10.

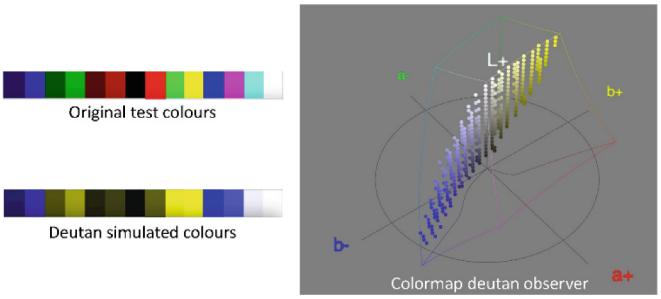

Fig. 10. Methods simplify colour representation by projecting colours from a three-dimensional space onto a subspace that includes the colour stimuli along the confusion lines.

Daltonization. Daltonization refers to the process of improving an image to compensate for missing information perceived by individuals with colour vision deficiency (CVD). Typically, this involves increasing colour contrast between colours that appear distinct to those with normal vision but are (nearly) indistinguishable to those with colour deficiency [48, 52–57]. A work by Green and Nussbaum introduced a daltonisation technique utilizing spectral filtering. They designed and implemented a spectral sharpening filter to enhance spectral reflectance for various colour pairs that individuals with CVD might struggle to distinguish. These reflectance pairs were transformed into colorimetry and displayed on a colour monitor, where observers assessed the visual contrast between the pairs through a psychophysical study. Findings indicate that an appropriate filter can amplify the disparity between red-green pairs [59].

Kotera [58] proposed a technique involving the restoration of spectral information lost to CVD observers through a spectral shift followed by an achromatic-preserving correction. This method begins by identifying spectra using a pseudo-inverse method derived from trichromatic data. In the initial step of the daltonisation process, a simulated version of the original image is generated. This simulated image is then subtracted from the original image in RGB space, resulting in an error image. Subsequently, the error image is added back to the original image, redistributing lost information to the green and blue channels (Fig. 11). Additionally, two main types of daltonisation methods can be distinguished:

Content-Independent and Content-Dependent methods. Content-independent methods do not ensure accurate colour differentiation for dichromats, as they employ a global pixel-based processing approach that disregards image content and spatial distribution of confusing colours. This uniform treatment of the entire image often leads to the creation of new confusing colour pairs or the remapping of distinct colours into indistinguishable combinations. On the other hand, content-dependent methods, including histogram-based, neighbourhood-based, and region-based techniques, consider the initial image

gamut, histograms, or pixel location in the image. Although these methods are more complex and computationally intensive, they yield better differentiation of coloured image elements. Simon-Liedtke and Farup assessed well-known daltonisation techniques through a behavioural visual-search approach [32].

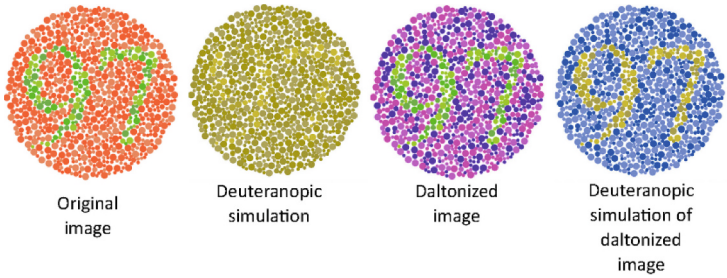

Fig. 11. A simulated version of the original image is created, then subtracted from the original in RGB space to produce an error image. Finally, the error image is added back to the original, restoring the lost information.

Conclusions. In conclusion, this section encompasses a comprehensive exploration of colour vision deficiency (CVD) and its associated topics. The introduction provides an overview of CVD, a condition characterised by difficulties in discerning certain colours due to abnormalities in colour-sensing mechanisms and the necessity of understanding its underlying mechanisms. Subsequently, the genetic basis of CVD is examined, with a focus on X-linked recessive inheritance patterns and the role of mutations in genes located on the X chromosome. The discussion then focuses on various types of CVD, such as protanopia, deuteranopia, and tritanopia, each featuring distinct alterations in colour perception and presenting unique symptomatic challenges. Exploring the concept of confusion lines, which connect colours perceived identically by individuals with CVD, underscores their significance in designing effective colour vision tests and developing accommodation strategies. Further examination involves an overview of methods for assessing colour vision in humans, encompassing pseudoisochromatic plates, anomaloscopes, and hue discrimination tests, along with their diagnostic applications. Lastly, the chapter introduces simulation techniques and daltonisation methods aimed at simulating and enhancing colour vision for individuals with CVD, emphasizing their potential to improve colour perception and overall visual experience in various environments.

3 Colour Perception Beyond Visual Stimuli

3.1 Synaesthesia and Cross-modal Experiences

The term "synaesthesia" is derived from Ancient Greek σύν syn 'together' and αἴσθησις aisthēsis 'sensation' and is the state in which a sensory (e.g. the sound of a note) or conceptual (e.g. a day of the week) stimulus causes, in addition to the corresponding sensation, some other involuntary sensation, a concurrent effect that we characterize

as a synaesthetic experience. This is a particular brain state experienced by certain individuals, its "pure form" affects a small proportion, between 0.05% and 4% of the world's population, the so called synaesthetes, who, because of their peculiarity, perceive the world in their peculiar way.

For some reason, in such a state there seems to be an interference between the sensory neurons of different senses, for example, the auditory neurons and the taste neurons. So, while listening to a melody normally activates the auditory cortex, which processes auditory information, it is also possible to simultaneously activate areas of the brain that process information about taste or even texture (touch). For example, listening to a high-pitched melody can be involved in triggering the sense of taste, and the synaesthete tastes an acidic, lemony taste at that moment.

Synaesthesia, according to Grossenbacher and Lovelace [60], is divided into (a) developmental, most commonly manifesting from childhood onwards and remaining relatively stable throughout life, (b) acquired and (c) induced by addictive substances, certain medicines or drugs (e.g., LSD). There are many types of synaesthesia, which are described by the formula x->y, where x is the triggering stimulus or motivator and y is the additional experience, a concurrent effect. Colour synaesthesia is the most common, and it is divided into subcategories such as grapheme->colour to a greater extent (where colourless printed letters, colourless numbers or colourless words are perceived as having an inherent colour), and the sound->colour (either music sound->colour or general sound->colour). Other types include auditory->tactile, sound ->emotion, lexicl->gustatory, etc.

Of particular interest is multisensory synaesthesia, where sounds and specific words evoke tastes, visual patterns and colours. Because of the multiplicity of synaesthesia types, as well as the different synaesthetic experiences of the same category between different individuals, it is not clear in what way one synaesthete understands how another synaesthete perceives things and what his or her aesthetics is. For these and other reasons, the phenomenon has been largely ignored by modern neuroscience and psychology, even though, beyond its intrinsic fascination, its understanding is important for understanding sensory perception and cognitive function [65].

Synaesthesia has been described as the union or synthesis of the senses or also as the most poetic disease. And because synaesthesia is not a painful experience, on the contrary, most synaesthetes know and value their peculiarity, are able to describe it in detail as fascinating, and would certainly not rush to be cured if a therapeutic method could be found. Moreover, Theodor Adorno (1903–1969) pointed out that the appearance of a phenomenon, such as synaesthesia, is often perceived as an abnormality, whereas in fact, it functions as a privilege in the conception and enjoyment of art. According to him, we consider synaesthesia as a perceptual deficiency because we isolate and exaggerate an element that is more or less common to all human beings: the perception of the world through the cooperation of the senses.

Synaesthesia is a particular and curious state of the physiology of perception, but beyond physiological synaesthesia, there is also "metaphorical" synaesthesia. The

metaphorical, rhetorical forms of synaesthesia, which are mainly associated with language, concern all of us. Almost all people associate different sensations with metaphorical speech, for example, saying that red is a 'warm' colour, that Helen has a 'sweet' face, or that someone has had a 'hot' argument.

3.2 Synaesthesia in Art

It is believed that synaesthesia is more common in artists or poets than in the rest of the population. Since a key element of creativity is the ability to connect two seemingly unrelated areas or thoughts to reveal a hidden underlying affinity, it is not surprising that some interpretive theories of synaesthesia, such as that of cross-activation or interconnection between cortical areas of the cerebral hemispheres are invoked to explain the creative ability of artists. Synaesthetic art often refers to multisensory experiences such as the visualisation, often with colour, of music, audiovisual art or abstract film. In this sense, synaesthesia in art is seen as the simultaneous perception of two or more stimuli converging in one experience.

The concept of synaesthesia has been used both by artists who were synaesthetes and explored their synaesthetic experiences to create a work of art and by artists who used it in its metaphorical sense, to create synaesthetic associations. Many artists, synaesthetes and non-synaesthetes, have tried to link the different senses, especially the perception of sound and colour, to attempt to create synaesthetic experiences without appealing to a synaesthetic audience, although it is not very clear why non-synesthetes' perception is enhanced by such connections. Twentieth-century artists such as Marc Chagall, Wassily Kandinsky or Henri Matisse, Paul Klee or František Kupka, who sought visual equivalents for concepts borrowed from music, such as rhythm/tempo, harmony, symphony or dissonance, resonance or counterpoint, coupled music and visual art in extraordinary ways. On the other hand, musicians such as Claude Debussy, Gabriel Faure or Rimsky Korsakof expressed the visual world through music. Both paths could have as their axis synaesthesia, in the sense of a connection of the senses, but which ends up as a connection of the arts, or perhaps the concept of "Gesamtkunstwerk" or "Total Art" as proposed by Richard Wagner.

The boundaries between synaesthesia as a neurological phenomenon and its metaphorical use in the context of medicine are clear, but not in art. It is very difficult to distinguish whether a work of art is the result of a synaesthetic experience on the part of the artist, or whether the artist has the perception and the talent to seek forms of expression that deliberately remove the boundaries between the arts, and in this way succeed in expanding the boundaries of the perception of art. Synaesthesia - physiological or metaphorical - is a source of inspiration for visual or musical artists, writers and poets in their art, while synaesthetic works themselves are for the general public a trigger to admire the mysteries of the mind (brain) [62].

And if synaesthesia has been a real driving force or only a source of inspiration in the creation of art that removes the boundaries between sensations and aims at perception as a holistic experience, how can we not consider synaesthesia as a precursor of the current search for artistic expression in the realms of immersive experiences and multisensory engagement? Chromesthesia, also known as sound-colour synaesthesia, is based on the phenomenon in which those who experience it (less than 1 in 2000 people) hear

colours and see sounds. Generally, those who experience chromesthesia also have perfect intonation or have perfect pitch, that is, by listening to a note they are able to know exactly which note it is. This is likely because they know which colour each note represents. There are several studies that address and deepen this issue, but, to date, there are few that talk about how the introduction of phenomena such as chromesthesia within interactive experiences related to cultural heritage can positively affect accessibility. In the following section, we will add relevant studies and experiences which Relate Colour to Sound.

Sound to Colour Mapping. In 2017, Dr. Bradley D. Meyer describes about how we can see the world in colour in relation to sound, exploring the relationship between the two and how the sound spectrum can be mapped to colours, both being waves which are measured in frequencies.

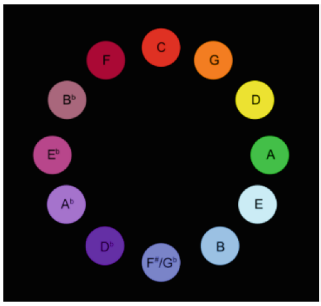

Fig. 12. Scriabin's *circle of fifths*

The idea of how to visualise this relationship had already been described in books on neuropsychology. The author analyses "synaesthesia", a phenomenon experienced by only 1 in 2000 people (e.g., even the well-known composer Scriabin) and there is no single definition. The author describes individuals who can "feel" colours and writes:

- *"they may see a specific piece of music or a chord or scale as being blue or green"*
- *"Interestingly the colours are not necessarily uniform across those with synaesthesia that equates sound to colour: One may see D major as blue, another as green, red, or yellow"*.

By mapping the association of colours "felt" by Scriabin with the circle of fifths, it is possible to notice an almost perfect gradient (Fig. 12). The author concludes the article by describing how colours are already widely used in music software (e.g., Iris, SpectraLayers, Metasynth, Audiopaint) to intuitively represent the amplitude or other characteristics of the sound wave.

Soundcolourproject (SOVIS). It is an experiment conceived by Kevin Groat and Derek Torsani with the aim of guaranteeing accessibility to music using visual attributes such as light, colour and texture, thus exploring multisensory accessibility. SOVIS (https://soundcolourproject.com/) can be accessed by having: a device, a microphone, an audio

interface, access to the website or by installing the app. It offers different ways of "translating" sound elements into visual elements, such as chromesthesia, chakras, emotion, chromotherapy, etc. The authors propose various applications for use, from musical performances to vocal visualisation and Chromotherapy Healing.

Play a Kandinsky. Google Arts & Culture launched this experiment in the form of a minigame by asking the question "*What if you could hear colour*?" and involving several of the most famous works by Wassily Kandinsky, a well-known painter of the Bauhaus period who probably had chromesthesia, a condition that allowed him to feel his paintings, with each colour and shape connected to a sound, a volume and an intrinsic tone. The project involves a narrative voice and simple instructions for use. All sounds are interpretations of artists who wondered what Kandinsky might have heard while he was painting some of his most famous works. At the end of the online experience, the user is given the opportunity to select which emotions gave rise to the painting he has just seen (Fig. 13).

Fig. 13. Play a Kandinsky minigame by Google Art[2]

The Colour of Sound. Flutopedia website has dedicated an article (2010, revised until 2016) dedicated to the nature of sound and colour and to how they are interconnected. The author describes how it is useful in many contexts including treatments for synaesthesia, music education and therapy, and meditation. Basic aspects related to sound (e.g., vowels used during vocalisations, musical intervals) can be connected to colour using pre-existing models, such as a direct relationship (e.g. tone ⇒ colour, where each tone has a colour, but not all colours can be mapped to a tone), or an indirect relationship, through the introduction of an intermediary with the purpose of acting as a link between the two. The author mentions the Chakra system, describing how the indirect relationship between colour and tone is affected through the correspondences, precisely, with the Chakras (Fig. 14). On the other hand, the author talks about the correspondences mapped by Scriabin (see Fig. 12), explaining how the composer placed similar colours on notes separated by a perfect fourth and a perfect fifth. At the end of the article, it is included a Clint Goss' pitch-to-colour calculator[3], which provides a visual representation in the

[2] https://artsandculture.google.com/experiment/sgF5ivv105ukhA.
[3] http://flutopedia.com/sound_colour.htm.

form of colour based on the chosen note, frequency standard used, etc. For example, choosing an A4 as Fundamental Note, the resulting colour is #ff4d00 and the calculator provides the following information: the resonant colour of light that is 40 octaves above an A4 at a pitch reference A4 = 436 has a frequency of 479.39 THz. This colour has a wavelength of 625.37 nm. The equivalent RGB colours (shown above) that approximate this colour of light are #ff4d00, based on a modified version of Dan Bruton's colour approximation algorithm.

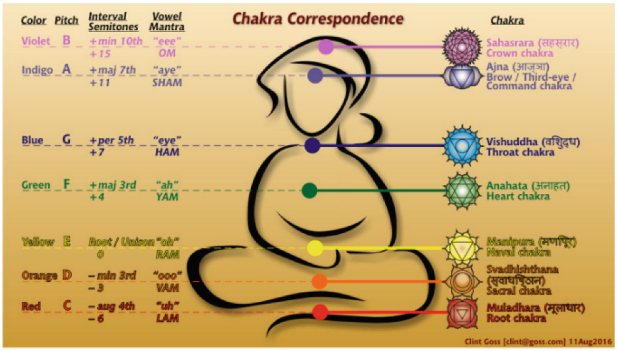

Fig. 14. Colour-tone correspondences based on the height of the Chakras

80 Hz Project. This project aims to explore the image catalogue of the New South Wales State Library through sound. The idea is linking sounds to images to suggest how the latter could sound like. The authors use "data sonification", already used in astrology and oceanography as a model for understanding large amounts of data: this allows those who do not have the ability to see the images to appreciate them in an innovative way. The project has produced an installation that has a curved wooden structure covered with anodised aluminium shingles. Inside the structure, a central mechanism displays a selection of paintings on a reel (similar to an Instagram feed). Visitors can turn a handle to select an image and listen to its dedicated soundscape. The audio is multi-channel in order to create an immersive experience by resonating within the structure, created specifically to generate reverberations. The translation of images into sound elements took into account visual data such as: complexity, colour, tone and face detection and metadata such as date, location and subject. The compositions are computer-generated (Fig. 15).

Jukepix (2018). In 2018, the authors of this project faced the challenge about how to transform paintings into music and proposed a cross-modality model to transform images into multitrack music based on Deep Convolutional Generative Adversarial Network (DCGAN), and unsupervised tasks. The proposed model is trained on a classical music dataset and an impressionist painting dataset and can be applied to transfer impressionist paintings into two-track classical music. Using music evaluation methods, the harmonicity of the generated music can be confirmed. The studio uses the "MuseGAN" project, which allows you to generate music of a length of 4 bars starting from a random noise.

Fig. 15. The wooden structure of the 80Hz project[4]

The model proposed in the Jukepix study allowed AI to establish a method of transformation between two art forms (Fig. 16). In the future, the authors hope to improve their model by combining solo instrument tracks with orchestral tracks to generate concert music [63].

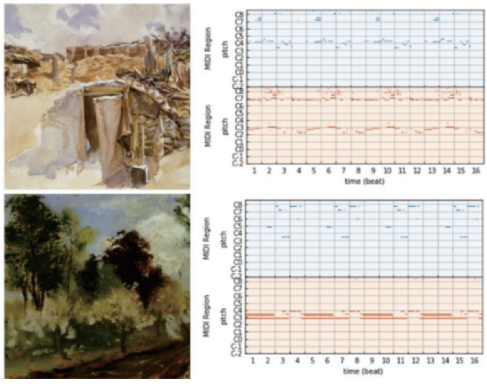

Fig. 16. Paintings and corresponding musical segments[5]

GANs N' Roses (2022). The project, accessible on GitHub[6], aims to make art even more usable by allowing users to experience it through other senses, in their case hearing, transforming a painting into a melody. Firstly, the picture under analysis is introduced into a convolutional neural network (CNN) which can predict possible emotions (20 different ones) aroused in visitors. Secondly, databases containing melodies associated with the same categories of emotions are defined in order to create a system for subsequently translating the images. Finally, the machine learning models created by the team are able to generate new sound content (Cobo 2022, Salu GitHub).

[4] https://www.youtube.com/watch?v=vXyrvWKzMVI.
[5] https://www.youtube.com/watch?v=AURD8NN-6iQ.
[6] https://github.com/GANs-N-Roses.

3.3 The Perception of the Artistic Message Through Colours

As anticipated, archaeological evidence shows that even modern humans' ancestors already used a variety of pigments [64–66], some for symbolic purposes. Why did humans, from the beginning, colour an already colourful world? Paleoanthropologists believe that, while there could be many reasons, at the core was a communication function [67] and the relation we have with colour is connected to the way we survive in this world [68]. Overall, the human vision system's goal is to seize from the continually changing information reaching the brain the most fundamental data, and there are certain kinds of knowledge, such as the colour of a surface, that can only be acquired through it [69]. According to Zeki, the functioning of the brain, and its mechanisms of perception, are governed by an active and continuous process of seeking the essential and an effort to distinguish the eternal from the desperately ephemeral. The essential, however, is nothing other than the pre-existing (Platonic) Idea within us, which, always according to Zeki, is identified through the archive of forms and states that the brain has recorded. And does not the same happen with art, as well? Is it not from this archive that the creations of artists emerge? For this reason, to understand art perception as well as to perceive colour in art, it is essential to consider perception as an inner and holistic operation of the brain. Additionally, the experience of colour is a subjective, relative, and unstable process. Josef Albers called colour "the most relative medium in art", and Henry Matisse said that "seeing is already a creative operation, one that demands an effort" [70]. Although they were not speaking neurologically, these statements express a neurological truth about the experience of vision. In fact, the context in which a perceived object is presented heavily affects the perception of colour [15]. Additionally, colour perception is an unstable and contestable phenomenon shaped by social and material factors [71]. Colour perception, in this view, is a social experience [72]. The experience of colour is deeply grounded in cultural meaning. For anthropologist Victor Turner (1920–1983), colour use is socially patterned, and reflective of basic life-and-death processes and emotions [73]. Sociologist Rose-Greenland sees colour perception also as socially patterned: colour can signal adherence to gender norms, political alliances, age, religion and marital status [74]. Colour has long-lasting cultural meanings. Colours even affect mood, which explains the careful attention that institutions pay to principles of colour harmony in public spaces [75]. The cultural currency of colour allows for a conceptualization of colour as material. Rose-Greenland finds three reasons for doing so: she sees that to trade on immaterial sensations, we need to materialise them; second, she believes that materialising colour perception draws attention to the importance of temporality, specifically the instability of colour; finally, materialization allows for the use of analytical parameters that comprise cultural objects [71].

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