CHAPTER 2 THE HUMAN VISION SYSTEM

Human vision system (HVS) is the second important aspect of studying colour. While physical processes produce and transform SPDFs, the definition at the beginning of Chapter 1 makes it obvious that colour is the response of the human vision system to these external electromagnetic stimuli. The eye *responds* to the SPDFs and the brain *interprets* them as colours.

HVS consists of the eye-brain system, its connecting optic nerve and visual pathways. It is a highly non-linear system that produces several complex visual responses, which in turn, greatly enhance the chances of our surviving the often dangerous environment around us. The eye is the sensor and generates responses to visual stimuli. These responses travel all the way to an area of the brain called the *visual cortex* which is located at the rear of the brain above the cerebellum (see Figure 2.1). The optic nerves from the two eyes meet in a region called the *optic chiasm* where the responses from the two eyes are combined and then split into two *halves* of the visual field. The right half of the visual field is processed by the left visual cortex and the left half by the right visual cortex. Along the way, the two halves of the visual field travel through a region of the brain knows as the *lateral geniculate nucleus*(LGN) which splits the information in the visual field into two parts: (i) depth and motion, and (ii) colour and edges. The depth/motion and colour/edges information from each half of the visual field is carried to the visual cortex. The visual information is interpreted in the visual cortex and finally processed by the *visual association cortex* to take necessary motor or other actions.

2.1 Retina and its Characteristics

The eye, shown on the left in Figure 2.2, is the sensory organ for the visual system in which the *cornea* and the *lens* are the focussing optical elements. The cornea accounts for nearly 90% of the focussing function. An inverted image is formed on the *retina* at the back of the eye. The retina is a multi-layered and extremely

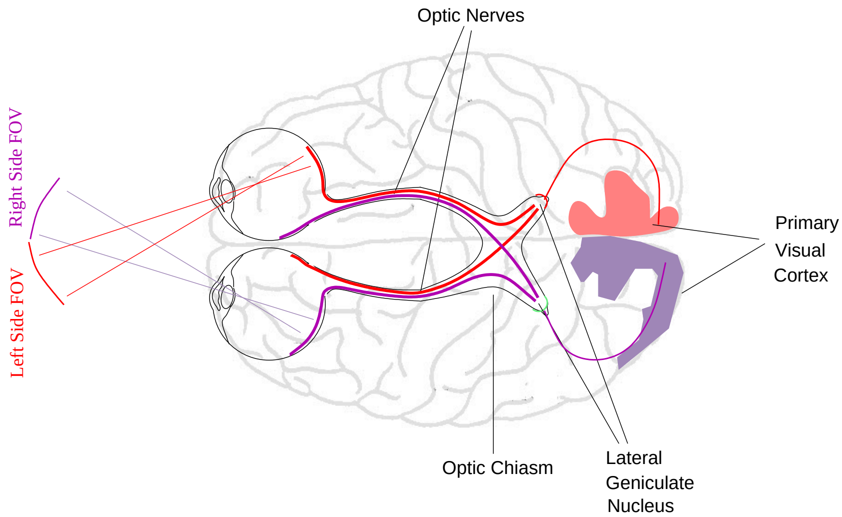

Figure 2.1: *The Human Vision System showing the visual pathways from the eyes to the brain*

complex tissue with light-sensitive special cells called *rods* and *cones*. The retina is about 25 mm in diameter in an adult human being and is nearly 75% of a circular arc. It is roughly 0.25 mm thick although the thickness is not uniform. Almost directly behind the opening of the eye is a special region called the *fovea* containing the highest density of photo-receptor cells. It is also the thinnest part of the retina. The *optic nerve* which conveys the visual information from the eye to the brain is

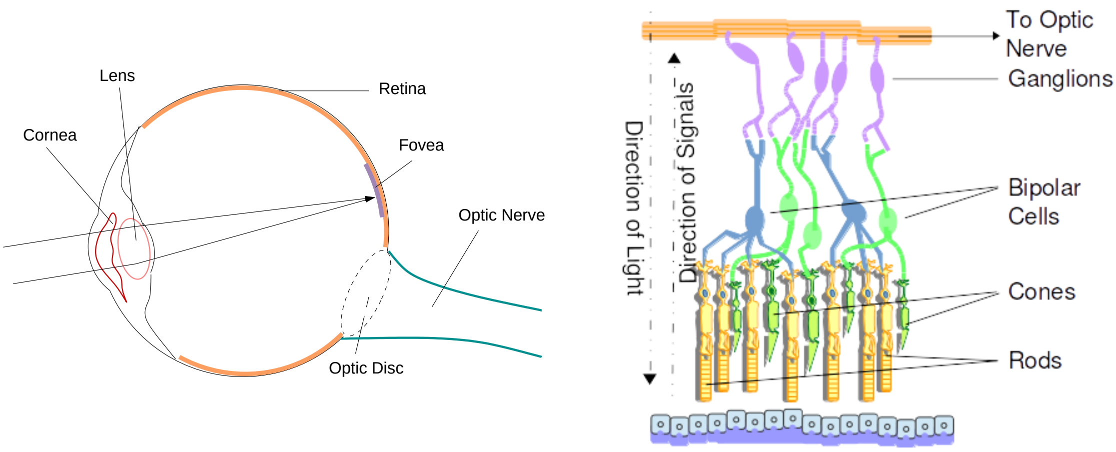

Figure 2.2: LEFT: *Structure of the eye showing the important parts: cornea, lens, fovea, optic disc and optic nerve.* RIGHT: *a cross-section through the retina showing its different layers.*

attached to the retina. The region where the optic nerve connects to the retina is called the *optic disc*. It does not contain any photo-receptor cells and the part of the image that falls on this region is not perceived by us.

The retina is the most important part of the eye and many optical phenomena may be explained by studying its structure. Retina is a living tissue with blood vessels for supplying blood, the photo-receptor cells: rods and cones, the foveal region and the optic disc.

Retina consists of several layers but their arrangement is counter-intuitive (see Figure 2.2 (Right)). The light sensitive rods and cones are not present in the top layer but are almost at the rear of the retina. There are about 150 million rods and nearly 7 million cones. The upper layers consist of *ganglion* cells, *bipolar* and *horizontal* cells. These layers are transparent to incoming light so that it passes through to the rods and cones without any distortion or significant loss. The ganglion cells pass messages to the optic nerve while the bipolar and horizontal cells appear to do primitive image processing. For example, these cells may detect edges, corners and orientations of the objects in the image. Moreover there are about 150 million receptors (rods and cones) but only about 1 million optic nerve fibres which means that the upper layers do some spatial aggregation of the signals from the receptors. It is also known that ganglions in a certain region can inhibit the responses of ganglions from another region.

Cones are the cells that provide us with colour vision. There are three types of cones: short-wavelength of *S* cones, medium-wavelength or *M* cones and long-wavelength or *L* cones. These are also sometimes referred to as *blue*, *green* and *red* cones. Almost all the 7 million cones are concentrated in the fovea. Cones require high intensity of light for activation. Thus, colour vision is found only when sunlight or a sufficiently powerful artificial lighting is used. Such vision is called *photopic* vision. The retinal pathway combines the response of individual cones before passing them on to the optic nerve. However, the responses of fewer number of cones are combined when compared to rods. As a result, cones provide us with high spatial acuity and allow us to distinguish fine detail. Cones are also directionally selective and our colour perception depends on where we are looking.

Rods are not sensitive to colour but only to overall intensity, i.e., brightness of the incoming light. There are relatively few rods in the foveal region and they increase in number as we move away from the fovea. The maximum density of nearly 150,000 rods/mm^2 occurs in a ring about 20° around the fovea. Rods are larger in size than the cones. The retinal pathway for rods combines or integrates responses from many rods before passing them on to the optic nerve. The larger size and the greater convergence of responses leads to the high sensitivity of rods to low light. But, it comes at the cost of lower spatial acuity: we cannot see fine details with rods. Under poor or low illumination conditions, such as on a moonlit night or under candle-light, only the rods (with their greater sensitivity than cones) are stimulated. At such times, we can see the different objects around us but will not be able to view their colours or fine details. Such vision is called *scotopic* vision.

Figure 2.3: *A statue of Maxwell and his colour wheel (in Edinburgh, Scotland), Thomas Young and Hermann von Helmholtz.*

2.2 Theories of Colour Vision

There are three main theories for explaining how the cones in the retina produce colour vision in humans (and primates in general): *Trichromatic Theory* of Maxwell, Young and Helmholtz; *Opponent Colours Theory* proposed by Ewald Hering; and, the *Modern Colour Theory* based on the work of Gunnar Svaetichin.

2.2.1 Trichromatic Theory

Thomas Young, in 1802, postulated that there exists three types of colour sensitive cells in the retina (we now call them cones) each being sensitive to a different range of wavelengths in the visible spectrum. Hermann von Helmholtz later in 1850 classified these three as short-, medium- and long-preferring based on their sensitivity to the incoming wavelengths of light. The brain combines and interprets the different strengths of responses from these three types of cells as colour. James Clerk Maxwell in 1855 took these ideas further. He was inspired in his work by Professor David Forbes's colour tops. These are tops having several colours painted on them which, when spun, would give the appearance of having a single colour. Maxwell made several spinning wheels (see Figure 2.3), each with three colours having different areas, and spun them to generate other colours. He adjusted the areas of the three colours, until the resulting single colour seen on the spinning wheel matched a reference colour. He would then write down the relative areas that resulted in the match. Today, his experiments are seen as precursors to the now famous *CIE Colour Matching Experiments* of 1931 (see Chapter **??**).

Maxwell, in 1861, also took what may be the world's first colour photograph in effect demonstrating practically the additive trichromatic theory of colour. He had the photographer, Thomas Sutton, take three black-and-white photographs of a colourful ribbon once each with red, blue and green filters. The resulting three photographs were then projected on to a screen using three projectors—one with a red light, a second with blue light and the third with green light. When the three images on the screen were correctly aligned, they showed the image of the original ribbon in full colour! Thus, Young, Helmholtz and Maxwell are credited with developing the *additive, trichromatic* theory of colour. While the trichromatic nature of colour vision had very few doubters, the hypothesis that three separate images being sent to the brain appeared very inefficient and also failed to explain several optical phenomena (see end of this chapter).

2.2.2 Opponent Colours Theory

In 1892, Ewald Hering (1834–1918) proposed a fundamentally different theory of colour vision from the additive trichromatic theory. His theory was based on certain observations about human vision.

- Humans see many shades of colours such as bluish-green, greenish-yellow, yellowish-green, etc. but never combinations of blue and yellow or red and green. There are no greenish-red, reddish-green, bluish-yellow and yellowish-blue shades.

- If we stare at a patch of red colour for sometime and then look away from it at a white region, we see an afterimage in greenish colour and vice versa (see Figure 2.4). Similar afterimage pairs occur with blue and yellow colours.

- When a green object is on a red background, it appears greener and a red object on a green background appears redder. Similarly, a yellow object on a blue background appears yellower and a blue object on a yellow background appears bluer (see Figure 2.4). For example, the Sun appears yellower than usual when there is a clear blue sky.

Hering sought to explain these phenomena by hypothesising three types of *bipolar* receptors. A bipolar receptor responds postively to one stimulus and negatively to its opposite stimulus. He stated that the photoreceptors in the retina have bipolar responses to light-dark, red-green and yellow-blue. It is clear that such receptors can never give rise to reddish-green, greenish-red, bluish-yellow or yellowish-blue responses. The afterimages are also explained using the adaptation of the visual system (see the end of the chapter). Hering's theory gives a very natural explanation for the three phenomena listed above. However, at that time, Hering's theory did not receive much positive reception because many scientists thought that is was not physiologically feasible.

2.2.3 Modern Theory of Colour

The modern theory of colour is really a combination of the additive trichromatic and opponent colour theories. Physiological support for Hering's opponent colour theory was first provided by Svaetichin's experiments in 1956 on goldfish. Goldfish have trichromatic vision and Svaetichin discovered that there are bipolar cells in their retinas. Later experiments revealed the presence of bipolar cells and opponent response pathways in the vision systems of several higher animals including macaque monkeys. These results led to the development of the modern theory of colour, sometimes called *stage theory*.

In the modern theory, colour sensing occurs in three stages. The photoreceptors in the retina, the cone cells, are trichromatic as postulated by Young. Their peak sensitivities are at 440 nm (blue), 560 nm (green) and 660 nm (red) as hypothesized by Helmholtz. However, the three signals are not transmitted to the brain directly. Light passes through the retina from the top to the bottom (as in Figure 2.2). The responses from the rods and cones in the bottom layer rise up to the previous layer that encodes the cone responses into three different signals. One signal is the weighted sum of the outputs of the three cones (S, M and L). The weights reflect the relative populations of the three cone types. A second bipolar (*opponent*) signal is red-green obtained by subtracting M cone response from the other two. The third is the bipolar yellow-blue signal obtained by subtracting S cone response from the other two. These three signals are independently transmitted by three separate retinal pathways via the optic nerve. Thus, colour vision starts trichromatic but is transformed into opponent signals.

It is also known that the contrast sensitivity, i.e., the ability to distinguish

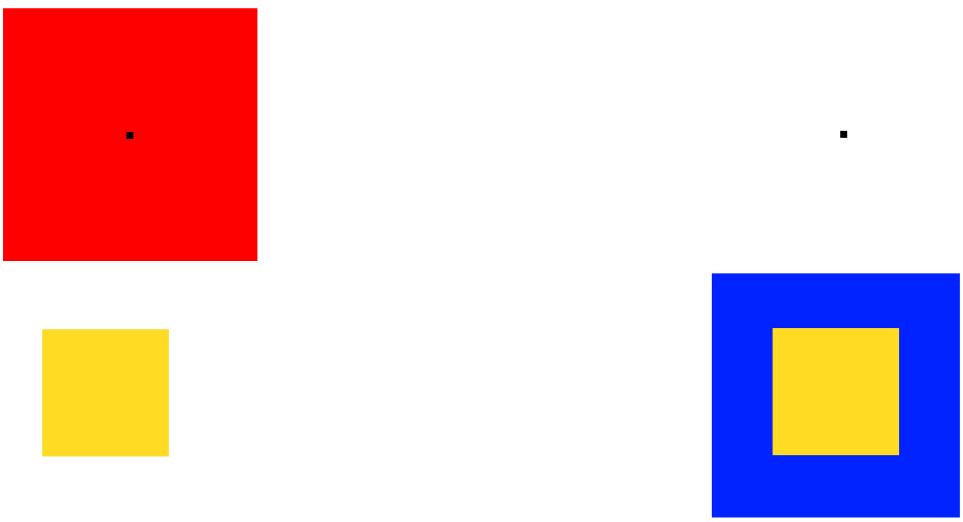

Figure 2.4: *Demonstrating certain visual phenomena. Stare at the black spot at the centre of the red square for about 20 seconds. Then, look at the black spot on the right side. You will see a bluish-green square afterimage. In the bottom figures, notice that the yellow square on the blue square appears lighter and brighter than the one on its left although both have the same colour.*

subtle changes, is more for the luminance signals than for the colour signals. The signals are also low-pass filtered before transmission to the brain. The peak sensitivity for luminance signals occurs around 5 cycles/degree and falls to zero beyond 60 cycles/degree. That is, details finer than 60 cycles/degree cannot be resolved

Figure 2.5: *Humans are more sensitive to changes in luminance than colour. Original image (top). Effect of blurring the image luminance (bottom-left). Effect of blurring the colour information (bottom-right).*

by the vision system. Colour signals also exhibit similar characteristics but their cut-off frequency beyond which they lose their sensitivity is much lower than that of luminance signal. Thus, our sensitivity to changes in colour is quite low. Figure 2.5 shows this effect quite dramatically. The first figure shows the original image. The image in the middle is obtained by blurring the luminance information. The blurring effect is clearly visible. The third figure shows the effect of blurring the colour signals while leaving the luminance unchanged. It is seen that we do not see much change from the original even though the blurring is the same as in the middle image.

A few other interesting details are also known about the different cells in the retina. The ganglion cells exhibit *centre-surround antagonism* in both spatial and spectral domains. Remember that a ganglion cell receives inputs from several photoreceptors (rods and cones). Centre-surround antagonism means that the input from a single rods/cone at the centre of a small region in the retina is enhanced while the inputs from its surrounding neighbours are suppressed (or *vice versa*). This sort of behaviour is quite familiar to students of image processing as *edge detector* and *Laplacian* kernels. Ganglion cells display such behaviour not only in the spatial domain but also in the spectral domain. For example, if the central cone generates a positive response for red colour, the surrounding cones are inhibited in their green response. Such a behaviour is probably responsible for increasing the dynamic range of both colour and black-and-white vision allowing us to see subtle changes in brightness and colour.

The rods are all of one kind and they have a peak sensitivity near 510 nm. Cones are of three kinds with spectral sensitivities covering the entire spectrum. The number of L cones is approximately 12 times that of S cones and 2 times that of M cones. Some researchers estimate that the number of L cones is 40 times that of S cones! Also, there are very few S cones and no rods in the fovea. Blue objects appear brighter than red objects in low light because the rods have greater sensitivity to shorter wavelengths. They may have the same brightness under bright lights.

2.3 Adaptation in Human Vision

A key characteristic of the human vision system, one that contributes to its high complexity, is that it is dynamic and *adapts* to the surrounding conditions. The range of illumination present in our environment is mind-boggling: consider the difference between a starlit night and a sunny afternoon; or the differences in colours in a peacock's tail and a colourful sunset! The adaptation mechanisms are present in our vision system so that we can navigate, negotiate, appreciate and enjoy our way through such a rich and wide range of illuminations and colours present in our life. The first mechanism that helps us adapt is the pupil of the eye. It varies in diameter from 3 mm to 7 mm in bright and dark conditions respectively. The amount of light hitting the retina changes by a factor of almost 6 as it is proportional to the area of the pupil. It is a very small adaptation and there are other more sophisticated mechanisms.

Three types of adaptations are important when studying colour. The first is *Dark* adaptation such as that when we walk into a dark room from a bright, sunny yard or when power goes out at night. Initially, the room appears completely dark and nothing is visible. Within minutes, we start to see objects in the room and soon almost all the bigger objects become visible. We are able to do this because our vision system is capable of adjusting its sensitivity to the surrounding illumination levels. The rods and cones raise their sensitivities in response to the lack of illumination. The cones are the first to adjust themselves and within a few minutes they attain their highest sensitivity and level off. This is the time when we see the bigger and brighter objects in the room. After the cones level off, the rods begin to dominate the vision by raising their sensitivity levels. The rods are slower but they have much higher sensitivity to darkness (i.e., their seeing thresholds are smaller than that of cones). Rods start showing an asymptotic behaviour after about 30 minutes and we do not improve our seeing much further.

The second is *light* adaptation which is the inverse of dark adaptation. It is discussed as a separate mechanism because of its significant differences from dark adaptation. Light adaptation comes into play when we go from a dark room into the sunny outdoors. The rods and cones reduce their sensitivities to handle the higher level of illumination. However, the adjustment is much faster and takes about 5 minutes rather than the 30 minutes needed for dark adaptation.

The range of brightnesses is very high and the rods and cones have a limited dynamic range. Researchers found that the human eye can detect roughly 25 shades of grey *around any given grey shade*. As the brightness changes, the vision system adapts itself so that it can see about 25 shades of grey at each brightness level. That is the dynamic range remains constant but the reference point moves to account for the changes in the ambient brightness or the shade being observed. If we analyse all the different shades that one can see, it is found that we can see about 220 shades in all. It is as if we have a whole family of brightness response curves each of which maps the available brightnesses in the immediate environment into the full dynamic range of the vision system which, with 25 shades, cannot independently span all the brightnesses at the same time.

The third mechanism is *chromatic* adaptation in which the three types of cones individually adjust their sensitivities to adapt to the ambient illumination or the colours being observed. Chromatic adaptation is the reason why a white paper remains white whether we view it in daylight, under fluorescent or incandescent lamps. Chromatic adaptation also gives the vision system an increase in the number of colour shades that can be perceived. Given any colour, we can see about 20000 colour shades around it. However, the vision system adapts to see 20000 colour shades, although they may be different, if we look at a different colour. Such an adaptation is responsible for us to perceive both the subtle shades of blue and green on a peacock's tail and the glorious reds and oranges of a sunset. It is not possible to enjoy the same level of detail if we have to observe both the peacock and the sunset together! Again, we can think of a family of colour response curves each mapping the colours in the environment to the available dynamic range. An appropriate colour response curve for the environment is chosen as required. With the chromatic adaptation, it is estimated that we may see around 10 million colour shades altogether.

2.4 Some Interesting Visual Phenomena

There are several features of human vision directly linked to the structure and characteristics of the retina. Come up with your own explanations for these before you look at Appendix A.

- BLIND SPOT: When we look at a scene, there is always a small region that cannot be seen by the eye. Such a region is called the *blind spot*. This is particularly important when driving a car using the rear view and side view mirrors to 'see' whether it is safe to turn. The blind spot is on the side and slightly behind the car one is driving and if there is another vehicle there, it is sure to cause an accident. There are many sites on the Internet which illustrate the blind spot: please see them.

- LOOK DIRECTLY TO GET MAXIMUM DETAIL: We have to look straight at an object to resolve the subtle shades of colour and fine detail.

- COLOURS INSIDE A ROOM WITH COLOURED GLASS WINDOWS LOOK "NORMAL" AFTER A FEW MINUTES: This effect is striking if you ever entered a room with green coloured glasses. The colours all look greenish when you enter such a room but after a few minutes, they begin to look natural again. For example, a white paper in such a room appears greenish initially but "becomes" white after a few minutes. More interesting is when you look out of a door or any other opening that does not have the green glass covering it: everything outside has a distinct *magenta* tinge!

  The same adaptation effect is shown in Figure 2.6. Stare at the black dot in the yellow coloured rectangle for about 20 seconds. Quickly look at the white dot in the bottom picture. You will see that the differences in colours between the two halves of the picture disappear. The boundary line (vertical) that you see near the centre of the picture vanishes!

- LOOK AWAY FROM A FAINT OBJECT TO SEE IT: This counter-intuitive suggestion is called *averted vision* that allows us to see extremely faint objects. This is particularly familiar to experienced star-gazers who use this trick to resolve very faint objects. If you are curious, try this for yourself in the months of November–December by looking for the great nebula in the constellation *Andromeda*. You can search the Internet for *M31 Andromeda Nebula* to get its location and how to find it.

- COLOURS ARE NOT DISTINGUISHABLE TOWARDS THE PERIPHERY OF THE VISUAL FIELD OF VIEW: Try it and see! While looking straight ahead, try to identify colours of the objects towards the right and left edges of the visual field.

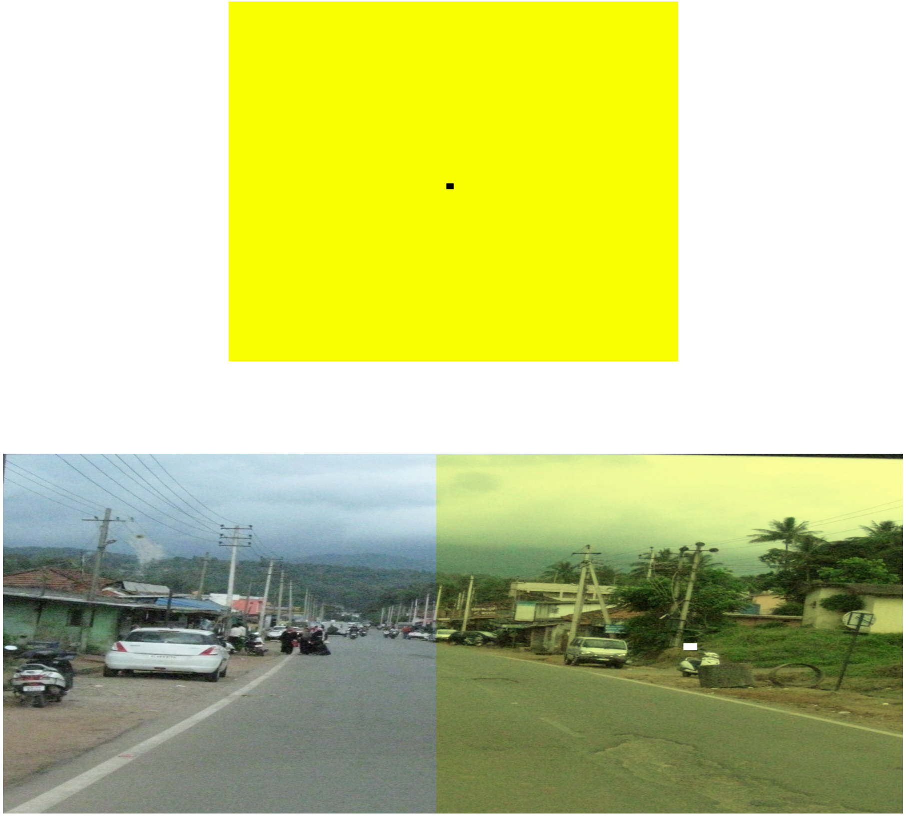

Figure 2.6: *Demonstrating colour adaptation of the human vision system.*

2.5 Summary

This chapter presented a brief overview of the human vision system comprising the eye and the brain. The structure of the retina and its relationship with various visual phenomena observed by us are discussed. Trichromatic theory of colour based on the early discovery of three types of colour sensitive cones and the opponent colours theory that came out of the necessity to explain certain visual characteristics are both presented. Modern theory of colour based on the work by Svaetichin on goldfish, a combination of ideas from the trichromatic and opponent colours theories, is able to explain all the observed visual effects of the human vision system. Many examples to illustrate the phenomena have also been presented in this chapter. The stage is now set for quantifying the interaction between SPDFs and elements of human vision to develop scientific and computational models of colour perception.