VISION IN-EXPERIENCE: INVESTIGATING THE INTERACTION BETWEEN THE CORRECT NON-PROTOTYPICAL COLOURS OF COLOUR DIAGNOSTIC OBJECTS AND OBJECT REPRESENTATION IN HUMAN OBSERVERS

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University
of
St Andrews

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3/27/2015

THIS THESIS IS SUBMITTED TO ST ANDREWS UNIVERSITY FOR THE DEGREE OF MPHIL

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Abstract

Hering (1964) hypothesized that the representation of a familiar object, which primarily includes its prototypical colour on the visual, conceptual and lexical domain may significantly influence how human observers organize the object's chromatic attributes – hue, saturation and lightness. Over the past years, studies concerned with the perceptual nature these objects (e.g. Duncker, 1939; Hansen, Olkkonen, and Gegenfurtner, 2006; Witzel, Valkova, Hansen, and Gegenfurtner, 2011) have been able to demonstrate that the colour knowledge which is mentally represented for certain groups of familiar objects does in fact modulate colour perception in cases when human observers are instructed to recover the absolute hue of these objects. Studies have also found that the mental representation of these objects in certain conditions influences the colour perception of unfamiliar objects (Mitterer and Ruiter, 2008). However, it is still a mystery whether the correct non-prototypical colours associated with certain groups of familiar objects are included in the representation of these objects and as a result influence the observer's ability to recover these objects' typical hue and typical hue category. Thus, in this thesis, I investigated whether correct non-prototypical colours associated with a certain group of colour diagnostic objects, that is, frequently experienced colour diagnostic objects, influence the human observer's ability to recover these objects' typical hue and typical hue category. In order to identify colour diagnostic objects, that is, objects with a constant object-colour conjunction, in the first experiment, observers were presented a range of objects and instructed to select as fast and as accurately as they can the colour they would typically associate with the presented object under normal conditions. The accuracy rate and decision-time scores, which correspond to the conditions a given object must meet in order to be considered a colour diagnostic object, were recorded for each object (Biederman and Ju, 1988). After identifying a group of colour diagnostic objects, an experiential rating scale was implored, with six phenomenological descriptors assigned a numerical value from 0 to 5 with the lowest descriptor assigned an experiential value of 0 and the highest descriptor – always, assigned an experiential value of 5. Objects with high experiential value (≥4) were referred to as frequently experienced colour diagnostic objects while objects with low experiential value (<4) were referred to as infrequent colour diagnostic objects. In the main study, which included four conditions – colour neutral, name neutral, name Stroop, colour Stroop - I measured how quickly observers were able to select the typical hue or typical hue category of achromatic frequently experienced and infrequent colour diagnostic objects, using an object Stroop decision-time task. The object representation of the objects phenomenologically categorized as frequently experienced colour diagnostic objects includes not only the prototypical colour typically associated with these objects but also the correct non-prototypical colour these objects are commonly experienced in. As for the representation of the objects phenomenologically categorized as infrequent colour diagnostic objects, the object representation of these objects only includes their prototypical colour. For this reason, I hypothesized that for the frequently experienced colour diagnostic objects, observers should take longer to recover their typical hue and typical hue category due to these objects' contextual associations which ultimately facilitates the mental activation of these objects' correct non prototypical colour. On the other hand, for infrequent colour diagnostic objects observers would be quicker in recovering the objects' typical hue and typical hue category as the activation of these objects' colour is non-contextual, which therefore leads to the activation of a single colour. In one out of the four conditions, results for the object Stroop decision-time task demonstrated that observers on average took longer to recover the typical hue but not the typical hue category for the frequently experienced colour diagnostic objects when compared to the infrequent colour diagnostic objects. In general, results from this study support the idea that the object representations of colour diagnostic objects not only include their prototypical colour on multiple domains (Naor-Raz and Tarr, 2003), but that their correct non-prototypical colours may also may be represented on the conceptual and lexical domain, additional information human observers are able to use as they quickly attempt to recognize these objects in atypical perceptual conditions.

Acknowledgements

“It is nobler to declare oneself wrong than to insist on being right - especially when one is right” — Friedrich Nietzsche. I dedicate this thesis to the philosopher Friedrich Nietzsche whose works have inspired me since the age of seven to devote my life to the relentless and tormenting pursuit of the truth without fear. I will also like to thank Oliver Penacchio for acting as my unofficial supervisor during this very long and painful journey in St Andrews.

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[1] All the figures taken from published sources has been cited, while the figures that are not cited are those that have been independently generated throughout the course of this thesis using the photo editing software GNU Image Manipulation Program (GIMP).

List of Tables[2]

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List of abbreviations

CDO: colour diagnostic object
CIE: Commission International de l' Eclairage
CNP: correct non-prototypical colour
ICDO: infrequent colour diagnostic object
FECDO: frequently experienced colour diagnostic object
LGN: lateral geniculate nucleus
MCE: memory colour effect
V1: primary visual cortex, striate cortex
V2: secondary visual cortex, extrastriate cortex
V4: visual area 4, colour area
MT: middle temporal, motion area

1 Chapter 1

General introduction

How does the human observer's subjective perceptual experience with a familiar object influence the human observer's ability to recover useful information about the object, namely the object's typical hue and typical hue category? I argue in this thesis that because certain groups of familiar objects – colour diagnostic objects (CDOs) - are typically associated with a single hue and generally constitute only a small percentage of objects surrounding human observers, for the CDO in question, the human observer is most likely to use the CDO's representation which primarily includes the object's prototypical[3] colour (Naor-Raz and Tarr, 2003). I also go on to argue that when CDOs are perceived as constituting a high percentage of the objects surrounding the human observers, this contextual association will most likely activate a much more dynamic representation of the object. In other words, unlike the CDOs associated with only a single hue, these objects' representations are much more dynamic, including its prototypical and correct non-prototypical colour which thereby influences how quickly human observers are able to recover these objects' typical hue and typical hue category.

In chapter 2, I will first explore how colour information is processed by the human visual system and how this process gives rise to the immediate experience of colour. This will be explored through a detailed analysis of the physiological response mechanisms of the retina to the sub cortical region - lateral geniculate nucleus (LGN), primary visual correct (V1) and the higher cortical regions of the visual brain. Towards the end of this chapter I will highlight the primordial task of the visual brain – acquiring knowledge about the important and constant properties of objects despite the state of flux their properties are constantly subjected to. I will go on to suggest that how the human visual system processes colour information and how the human observers chooses to assign fixed concepts and objects to an immediate experience of colour is intrinsically motivated by the primordial task the visual brain aims to achieve. In chapter 3, the term colour perception will be defined. Following this definition, I review a range of

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[3] While there are a number of ways the adjective prototypical is defined in various scientific works on prototypes, prototypical in this thesis is purely defined as the most commonly seen colour associated with the object, while correct non-prototypical colours are defined as the other set of colours in which these objects are also presented in, any other definition with respect to prototypical should be immediately suspended.

psychophysical studies concerned with the effect of colour names (or categories), colour knowledge or (memory colour) on colour perception. In the second half of this chapter, the focus of the studies reviewed is heavily criticized, particularly of the studies concerned with the effects of CDOs on colour perception as all of them primarily focus on the typical hue associated with these objects while completely ignoring the importance of the other hues commonly associated with these objects.

In chapter 4, CDOs will be reintroduced. I will first explain why it is important to investigate CDOs using a different theoretical framework and why the traditional framework, if we are to understand the nature of these objects in their entirety, that is, the adaptive role of these objects on emergence of primate colour vision and their role in our day to day visual experience (Regan et al, 2001). Next, the overall aim of the studies reported in this thesis will be provided. In the second half of this chapter, the techniques and methods used to design the studies reported in this thesis will be highlighted in great detail - from the importance of monitor calibration, colour space selection to stimuli generating. Following this, the methods and results of the preliminary study, which proved to be instrumental in identifying the CDOs used in the main study, will be reported.

In chapter 5, the second experimental chapter, I will investigate the effects of correct non-prototypical colours (CNPs) - secondary colours a subset of CDOs also appear in - on the human observer's ability to recover the typical hue and typical hue category of nine CDOs. Because the strong contextual character frequently-experienced colour diagnostic objects (FECDOs)[4] typically demonstrate when compared to infrequent colour diagnostic objects (ICDOs), I hypothesise that, on average, observers will take longer to recover these objects' typical hue and typical hue categories when compared to ICDOs. This hypothesis will be tested using an object Stroop task, similar to the one used in the study conducted by Naor-Raz and Tarr (2003) and with the same observers, used in part one and part two of the first experiment. The effects of CNPs on the object representation of these objects will be presented and following this is an in-depth discussion, highlighting the possible implications of these results in different colour related areas of research.

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[4] For an extensive definition of frequently experienced colour diagnostic objects, infrequent colour diagnostic objects, only and other terms adopted in this thesis, please see the glossary section of this thesis.

2 Chapter 2

Colour processing from the retina to the higher cortical regions of the visual brain

2.1 Introduction

In the most basic sense, the fixed and constant task assigned to the retina of the human observer (or primate[5]) is to capture different wavelengths of light in the physical world. The light captured by the retina is later processed by the intermediate and retinal ganglion cells. Visual information, namely colour information, processed up to this point is subsequently projected into the lateral geniculate nucleus (LGN) - a subcortical region in the visual brain while information processed in this region is sent via the optic nerve using optic radiation to the higher cortical regions – V1, V2, and V4 - for further processing, namely the integration of incoming sensory information which is later modulated by top-down information (Hupé et al, 1998). It is only after the completion of this fixed and extremely dynamic process that the perception of a given colour is afforded to the human primates. Within this chapter, I will briefly review how photons at a given wavelength is absorbed by the cells located in heterocellular retina of the human primates, starting from the rod and cone photoreceptor cells to the intermediate cells – horizontal, bipolar and amacrine cells- and the retinal ganglion cells. Following this, the organized manner in which colour information is processed and represented in order to be projected from the retinal ganglion cells into the higher cortical areas of the visual brain will be briefly highlighted.

2.2 Heterocellular retina

The heterocellular retina of the human primate evolved in order to absorb and record spatiotemporal, achromatic and arrangements of light. As a result of this, light at a given wavelength, which enters the eye of the human primate, is immediately refracted by the cornea (located towards the outermost part of the eye), crystalline lens (located towards the inner part of the eye, closer to the retina) and the iris (located in between the cornea and crystalline lens) (see Figure 2.1. for a complete look at the principal areas of the human primate's eye). The refracted light later passes through the vitreous body, eventually making its

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[5] The term observer is replaced with primate in chapter 2 because the classification fits well from a taxonomic stand point with the other species mentioned in this chapter. Following this chapter the term observer is used.

way towards the heterocellular retina, comprised of different types of cells, such as the sensory, gliaform and multipolar cells (Dagnelie, 2011).

Figure 2.1: The Figure is unavailable due to copyright restrictions.

The photoreceptor cells and bipolar cells make up the sensory type cells which are primarily responsible for processing and computing sensory information about the physical world to the different areas of the heterocellular retina. The gliaform type cells are made up of horizontal cells tightly horizontally glued to various cells in the heterocellular retina while the multipolar type cells, which made up the third cell type in the heterocellular retina, are made up of projection cells - ganglion and axonal cells with the addition of few local circuit cells (Marc, 2009). Because of the multiple dendritic spines and long axons these cells possess, the projection cells are able to project into the various areas of the heterocellular retina, eventually relaying useful visual information about the physical world to the subcortical and higher cortical areas of the visual brain. Similarly to these cells, the local circuit cells (or interneurons) are also instrumental in forming useful connections between different types of cells in the heterocellular retina. Unique to the local cells, however, is their ability to shape the neuronal circuit activity of various retinal cells, using the following neurotransmitters: GABA[6] and glycine (Marc, 2009).

Although different cell types in the heterocellular retina perform different tasks which are unique to their cell type, most retinal cells often work together during the processing of visual (or colour) information and thus are tightly vertically arranged into discrete layers, originally discovered by Ramon y Cajal (1892) (see Figure 2.2 which illustrates Cajal's classical drawing of the mammalian retina and its different layers). As a result of this tight arrangement, located underneath the retinal pigmented epithelium (RPE) – pigmented cell layer outside of the retina - is the outer nuclear layer (ONL) which contains the nuclei of the photoreceptor cells. Directly below this layer is the inner nucleus layer (INL) where the nuclei of the intermediate cells are located. In the ganglion cell layer (GCL), the nuclei of the ganglion cells are tightly packed together, while in the inner plexiform layer (IPL), the axon terminal of bipolar, amacrine and ganglion cells can be found in abundance (see Sung and Chuang, 2010 for an extensive discussion of the retinal cell layers). In light of this, the way colour information is processed and transmitted by human visual system from one layer to the next is highly influenced by the vertical structure of the retinal cell layers.

Figure 2.2: The Figure is unavailable due to copyright restrictions.

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[6] GABAergic and glycinergic are both inhibitory neurotransmitters observed in the HSV and thus responsible for regulating neuronal excitability (see Legendre, 2001, pg. 760, for a more extensive review).

2.3 Cone photoreceptors cells

There are two types of photoreceptor cells located in the ONL. The first type are the rod photoreceptor cells which make up about 95% of all the photoreceptor cells in the heterocellular retina of the human primate. The rod photoreceptor cells are particularly useful during scotopic conditions as these cells are optimally excited (or depolarized) when lower range of light intensities is captured by the human eye ((Sharpe, Stockman, Jagle, Knau, and Nathans, 1999). The second type of photoreceptor cells, which will be the photoreceptor cells primarily reviewed in this chapter, are the cone photoreceptor cells. Unlike the rod photoreceptor cells, these cells are primary responsible for photopic conditions and thus the initial processing of colour information. It is important to keep in mind that while the rod and cone photoreceptor cells are responsible for different conditions, they do at transitional period (or mesopic conditions) in order characterise the exact luminous levels during this shift also known as the Purkinje shift, from scotopic to photopic condition or vice versa (See Stockman and Sharpe, 2006 for an extensive review of the on the role of the cone and rods photoreceptors cells during mesopic conditions).

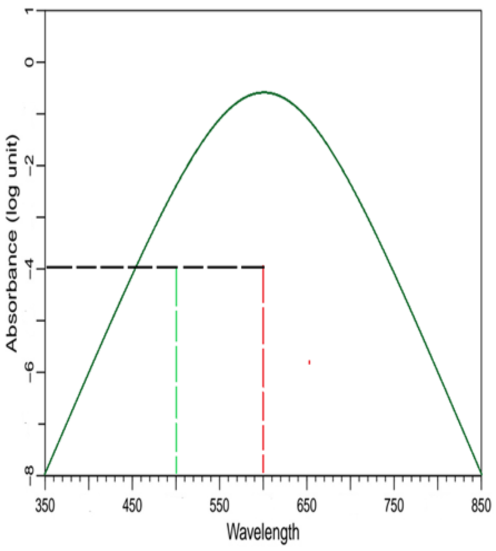
Futhermore because the human primate has three types of cone photoreceptor cells, human primates are commonly referred to as trichromats (Stockman, Sharpe, Jagle, Knau, and Nathans, 1999). These three types of cone photoreceptor cells are commonly referred to as small (S)-, middle (M)-, and long (L) - cones, denoting the spectral sensitivity (or absorption spectra) of each cone type. The S-cones, by shining light through the cornea, are primarily assigned the task of capturing shorter-wavelengths of light and make up less than 10% of the total cone photoreceptor cell population, with a maximum absorption capacity of 420nm or 440nm when estimated in vivo. The M- cones on the other hand are primarily assigned the task of capturing middle-wavelengths of light with a maximum absorption capacity of 530nm or 545nm when estimated in vivo. The L-cones has the highest absorption capacity when compared to the other cone type. These cells are shifted towards capturing longer-wavelengths of light with a maximum absorption capacity of 5558nm or 565nm when estimated in vivo (see Figure 2.3 for an illustration of the cone absorption spectra). Both M- and L- cones make up more than 90% of the total cone photoreceptor cell population, as it is reported in the study conducted by Linberg, Lewis, Shaaw, Rex, and Fisher (2001) on the distribution of cone types in mammals (i.e. young cats).

Figure 2.3: The Figure is unavailable due to copyright restrictions.

2.3.1 Univariance principle

Without the three cone types, primate colour vision is difficult and nearly impossible; such impossibility is best captured by the idea known as the univariance principle. In normal conditions, when light at a given wavelength is absorbed by a single rod or cone photoreceptor cell, the information captured by this cell is transduced (or converted) into voltage signals in the photoreceptor cell’s membrane which eventually initiates the hyperpolarization of the photoreceptor’s cell membrane (Fu, 2010). However, during the transduction of a given wavelength into voltage signals, without the presence of more than one photoreceptor cell, it is very difficult and almost impossible for a single photoreceptor cell to maintain the identity of the wavelength as well as the light’s intensity previously absorbed by the photoreceptor cell. The inability to recover the information, such as the wavelength type and intensity, is thus commonly referred to as the univariance principle.

To further highlight the importance of the univariance principle and the problem it poses to the human primate’s ability to experience colour, the graphs in Figure 2.4 are included. In the graph on the left, light at a given wavelength of 500nm and 600nm is captured by a single cone photoreceptor cell. Although two different types of wavelengths have been absorbed by the single cone photoreceptor cell in this hypothetical condition the wavelength type is not represented by the photoreceptor cell, generating merely a single 0.5 output. As a result of this, the single photoreceptor cell by is incapable of accurately relaying information about colour to the intermediate neurons – located in the INL - as it is unable to account for the difference in wavelengths (e.g. green light or red light). To make matters worse, the single cone photoreceptor cell is also unable to account for the intensity (or spectral power) associated with a given wavelength. In the right graph in Figure 2.4, there are two wavelength types – 460nm (green), 500nm (green), which have been absorbed by the single cone photoreceptor cell. For each wavelength there is an associated spectral power - +.5, +1, representing the intensity of each wavelength absorbed. Despite the fact that both wavelength happens to carry the same chromatic information, the luminous – that is the different spectral power associated with each wavelength is irrecoverable as the single photoreceptor cell is only capable of generating a single output. In other words, if we are to judge the signalled output generated by the photoreceptor cell in this hypothetical condition, it is impossible to know whether the green wavelength absorbed by the single photoreceptor cell is a light or a dark green. The ability to distinguish between the intensities of a given colour is central to human colour vision, as explained by Surridge, Osorio, & Mundy (2003) and was especially important to the catarrhine frugivorous primates with whom human primates share a common ancestor, often used this ability to distinguish between healthy – darker, and unhealthy – lighter leaves, constituting a high percentage of the objects surrounding these primates and thus being a was a viable source of diet.



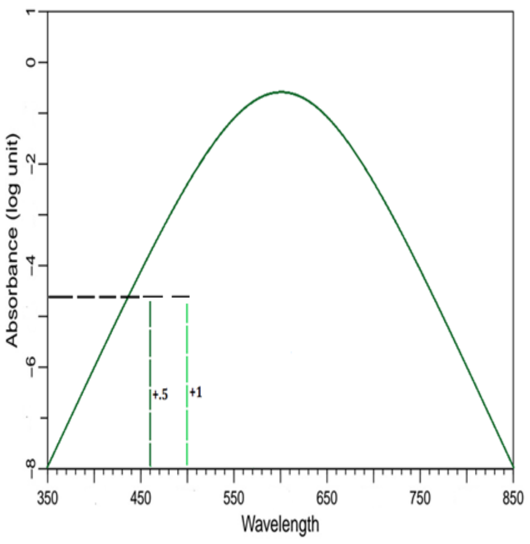


Figure 2.4: The left graph shows that when a single photoreceptor cell is responsible for absorbing the information of two distinct wavelengths, the response generated by the single photoreceptor cell (i.e. 0.5.) is the same (or singular) despite the fact that there are two different wavelengths responsible for initiating this response. The graph on the right shows two different wavelengths with its associated spectral power (or intensity). Similar to the graph on the left, a single photoreceptor cone is unable to capture information about the spectral power associated with the given wavelength (i.e. +5, +1).

2.3.2 Dichromatic vision

In order to deal with the problem of univariance, at least one other cone type capable of generating a different spectral output is needed. With the addition of another cone type, sensitive to a different wavelength of light, it is now possible to compute the ratio of excitation in two different cone types and thus recover the colours which make up a given spectral input. A subset (i.e. 1% of male European descent and 1 in 400 women) - of the population's colour vision, that is, dichromats, is based on only two cone types, cones which posses opsin pigment 364-amino-acid septa-transmembrane proteins, located on the external layer of the cells, allowing for the absorbing of photons of specific wavelengths (Neitz & Neitz, 2000). Human primates with dichromatic colour vison are also commonly referred to as protanopic, deuteranopic, or tritanopic depending on the abnormal or missing opsin photopigment (Stockman, Sharpe, Jagle & Nathans, 1999). Protanopic human primates have a genetic alteration in the genes responsible for encoding L– opsin photopigment. As a result of this, their experience of colour is only based on the following two cone types – M- and S- cone types. Therefore, when a red object in the physical world is being presented, human primates with dichromatic colour vison cannot correctly perceive the redness of that object as the L- cone type, primarily responsible for absorbing longer (e.g. red) wavelengths of light is missing. The absence of the L- cone type also contributes to these primates' inability to discriminate between greenish-blue and red wavelengths of light (Judd, 1948). Due to the absence of the red colour spectrum, represented in black, (see Figure 2.5 to view the colour spectrum of human primates with dichromatic, trichromatic, monochromatic and achromatopsia colour vison), these primates also have a shorter colour spectrum than the one of the normal human primate. As a result of this, their neutral point (or midpoint) is typically shifted towards a yellowish-blue colour as oppose to a greyish-blue colour as observed in normal human primates.

On the other hand, human primates with deuteranopic colour vison have a genetic alteration in the genes responsible for encoding M– opsin photopigment. Consequently, their experience of colour is based on the following two cone types – S- cone and L- cone. Because of the missing M-cone type, the appearance of green is virtually impossible. Similar to human primates with protanopic colour vison, these primates are also unable to discriminate between green and purplish-red colours while a shift in their neutral point towards a yellowish-blue colour is typically observed (Judd, 1948). As for the human primates with tritanopic colour vision, which is the rarest of the three conditions (less than 1% of the human population), a genetic alteration in the genes responsible for encoding S – opsin photopigment is typically observed. The absence of S- cone not only makes the appearance of blue colours impossible, but also makes it difficult for the human primates with tritanopic colour vision to discriminate between blue and greenish-yellow wavelengths of light. In addition to this, these primates typically have an extremely shifted neutral point corresponding to a yellowish-red colour (Judd, 1948).

Although the absence of a single cone type limits the dichromats from being able to experience a wider range of colours when compared to the normal human primate's experience of colour, there are far more extreme forms of cone deficiency which further limit ones experience of colour. It is, for example, possible to have an abnormality or absence of two opsin photopigment (M – opsin photopigment and S – opsin photopigment, M – opsin photopigment and L – opsin photopigment, or S – opsin photopigment and L – opsin photopigment), as discussed by Stockman, Sharpe, Jagle & Nathans (1999). This condition is commonly referred to as cone monochromacies. In an even more extreme cases, as observed in mammals-raccoons (*Procyon lotor*) and Kinkajou (*Potos flavus*), there occurs a complete loss of all three cone types. In this case, the appearance of colour is impossible as every single object represented in the physical world is experienced on a grayscale (or shades of black and white). This condition is commonly known as complete achromatopsia (or rod monochromacy) (Peichl, Behrmann, and Kroeger, 2001).

Figure 2.5: The Figure is unavailable due to copyright restrictions.

2.4 Intermediary cells

With the information reviewed above, it should be quite clear that several cone types with different spectral sensitivity are essential as the human visual system attempts to discriminate between different colours of light, crucial to the human primate's experience of colours. In the case of fewer cone types being present, the discrimination between certain colours of light will mostly likely be impaired. On the other hand, an increase in cone types, as observed in the human primate and the tetrachromats (four cones types), allows, when compared to the dichromatic observer, a higher discrimination power, which is in all critical to the initial processing of colour information.

It is further worth noting that in dichromats and trichromats - normal human primates, wavelengths of light absorbed and transduced by the S-, M-, and L- cone types, because of the closeness in absorbance spectral (e.g. M-, and L- cone cells), do not actually detect colour. Instead the difference between cone excitation must be computed and only after this is when the chromaticity and the associated intensity for a given object is obtained (von Helmholtz 1852). Once an excitation ratio is computed, this information is transmitted to the next layer of the heterocellular retina - INL - for further processing. Also the adaptive pressure which encouraged the emergence of M-, and L- cone types is largely still a mystery, however it is often argued that these cones evolved at the same time as flowering plants and fruits as the reflectance function of the fruits (i.e. colour diagnostic objects) they produced highly resembles the chromaticity these cells are responsible for computing (Allen, 1879; Polyak, 1957; Mollon, 1989). Furthermore within this layer are located the intermediate cells - horizontal, bipolar, and amacrine - the main cells which serve as intermediaries between the photoreceptor cells and the retinal ganglion cells, universally acknowledged as the last cell type in the heterocellular retina of the human primate (Cotran, Kumar & Collins, 1999).

Figure 2.6: The Figure is unavailable due to copyright restrictions.

2.4.1 Horizontal cells

Horizontal cells make up about 15% of INL cell population (Strettoi & Masland, 1995) and are directly connected to rod and cone photoreceptor cells through chemical synapses. A smaller percentage of these cells is also connected to other horizontal cells through gap junctions located in the OPL, towards the retinal ganglion cells (Troncoso, Macknik, & Martinez-Conde, 2011). Information about colour received by the horizontal cells from cone photoreceptors cells is either transmitted to the bipolar cells – the next group of intermediate cells in the INL - other horizontal cells, or back to the same cone photoreceptor cells information was initially received from. This lateral inhibition later helps to increase spatial differences when photoreceptor cells are activated, allowing colour information to be feed forwarded from cone photoreceptor cells directly to various bipolar cells in the INL, instead of taking the more conventional route - horizontal to bipolar cells (Kolb, 2003). During this feedback process as it was discovered by DeVries & Schwartz (1992) while investigating vertebrates (i.e. catfishes), dopaminergic neurotransmitters (e.g. dopamine) are released, allowing horizontal cells to modulate certain cone photoreceptor cells to become more sensitive to darker colours of light and less sensitive to brighter colours of light, when capturing subsequent wavelengths of light.

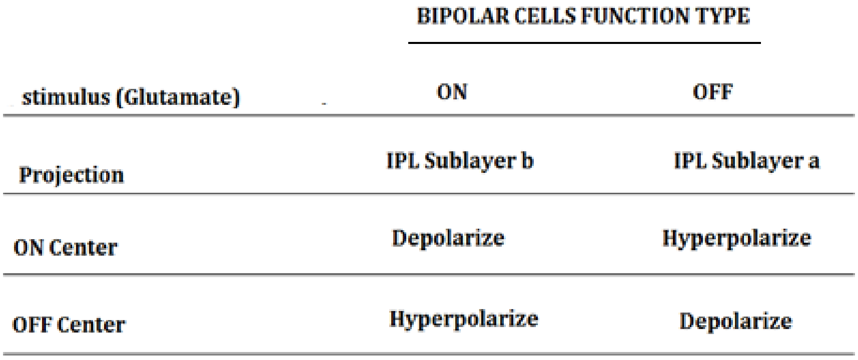
2.4.2 Bipolar cells

Bipolar cells make up the largest percentage of INL cell population – 41 %(Strettoi & Masland, 1995). Although bipolar cells receive information about colour from horizontal cells, majority of its input comes directly from cone photoreceptor cells. Unlike horizontal cells, bipolar cells evolved in a manner in which colour information is obtained from a single cone photoreceptor cell (Mcllwain, 1996). Originally discovered by Polyak (1941) there are two different types of bipolar cells in the human primate - parasol (or diffuse) and midget bipolar cells. Parasol cells are typically connected to multiple rod or cone photoreceptor cells, while midget cells are only connected to a single photoreceptor cone at a time. The point at which chromatic or luminance information is exchanged from one photoreceptor cell either through the pedicles (synaptic terminal for transmitting cone electrical signals) or spherules (synaptic terminal for transmitting rods electrical signals) to a given bipolar cell is commonly referred to as the traid – the dendrite of a given bipolar cell (McIlwain, 1996).

2.4.3 Bipolar cells receptive field (RF)

Morphologically bipolar cells have a surround region which opposes the centre of its receptive field (RF) – a visual field in which an illuminated stimulus is presented by a given retinal cell (e.g. horizontal or photoreceptor cell) to another retinal cell (e.g. bipolar cell). As was discovered by Werblin & Dowling (1969), the way a bipolar cell responds when luminous information is received in the form of glutamate –

most common excitatory neurotransmitter in the visual brain , either in the centre or the surrounding regions of the bipolar cell's RF, distinguishes between the two types of bipolar cells - ON and OFF bipolar cells. For example in the case when illuminated information is passing through the basal surface of the spherules and eventually received on the centre of a given bipolar cell's RF, some bipolar cells- ON bipolar cells, depolarize in response to the presentation of glutamate, resulting in an increase in the cell's membrane potential. On the opposing side are OFF bipolar cells, these cells when illuminated information passes through the basal surface of the pedicles, and eventually received on the centre regions of the cell's RF, these cells hyperpolarize causing a decrease in the cell's membrane potential. As a result of this response, the neurotransmitter glutamate is inhibited (McIlwain, 1996). Note that bipolar cells only depolarize when luminous information falls on the surrounding regions of its RF (see Figure 2.7 for ON and OFF bipolar cell's typical response to luminous stimulus). Colour information processed and represented by ON and OFF bipolar cells, critical to the human primate appearance of colour, is later transmitted to other retinal cells in the heterocellular retina namely the retinal ganglion cells.



	BIPOLAR CELLS FUNCTION TYPE	
stimulus (Glutamate)	**ON**	**OFF**
Projection	**IPL Sublayer b**	**IPL Sublayer a**
ON Center	**Depolarize**	**Hyperpolarize**
OFF Center	**Hyperpolarize**	**Depolarize**

6.1: This table is an illustration of the bipolar cells function type- ON and OFF bipolar cells. Notice the OS of the OFF and ON receptive fields of the bipolar cells which becomes a typical way in which colour information is represented in the retinal cells and in the cortical areas of the visual brain.

2.4.4 Amacrine cells

Another most important intermediate cells constantly modulating and redirecting visual information sent from various retinal cells in the heterocellular retina of the human primate are the amacrine cells, which makes up 32% of the INL cell population (Strettoi & Masland, 1995). Although there is still much to understand about these cells', there are at least five major types of amacrine cells known – glycinergic amacrine cells, GABA amacrine cells, biogenic amines amacrine cells, neuropeptide amacrine cells, and metabotropic amacrine cells with either a small, medium, or wide dendritic field – the main area which receives input signals from other retinal cells (Iezzi & Finlayson, 1996). The chemical compounds attached to an amacrine cell type denotes the chemical compound released as the amacrine cell modulates, that is, laterally inhibits, spatially tunes, interconnects or redirects retinal cells (e.g. other amacrine, bipolar, and ganglion cells) in the heterocellular retina of the human primate (Strettoi & Masland, 1995).

One of the most important amacrine cells, extensively studied over the past years, are the glycinergic amacrine cells. They have a small dendritic field and release inhibitory neurotransmitter glycine, as information processed in these cells is typically directed towards a given ganglion, amacrine or bipolar cell. In this case, glycinergic amacrine cells act as intermediaries, refining and connecting information sent from ON and OFF bipolar cells to ON and OFF ganglion cells for further processing. Another important group of amacrine cells are GABA (gamma-amino butyric acid) amacrine cells. These cells not only have a small dendritic field but also release the inhibitory neurotransmitters known as GABA. The most well-known GABA amacrine cells are the AII and A17 cells (Kolb, 2004). Because bipolar cells which receive visual information from rods do not have a direct channel to ganglion cells, AII and A17 cells, act as intermediaries, connecting rod based inputs from bipolar cells to ganglion cells - information which becomes critical during the computation and representation of darker colours in the physical world (Kolb, 2004).

2.5 Retinal ganglion cells

Intermediate cells described above, directly transmit critical information to retinal ganglion cells - cells which are ultimately responsible for transmitting colour information to the LGN and higher cortical regions of the visual brain.

Retinal ganglion cells are located in the GCL of the heterocellular retina and as a result of this they make up the last stage of retinal processing. There are at least twenty different types of retinal ganglion cells in the heterocellular retina of the human primate, 80% of its population being composed of Midget (or P cells) and Parasol (or M cells) retinal ganglion cells (Hildebrand & Fielder, 2011). Midget cells are tightly packed near the fovea and for the most part receive information from M- (green) and L- (red) cones, critical for processing information about colour. Information from S- cone photoreceptor cells are transmitted to the GCL differently as they evolved much earlier in the human primate evolutionary history (Kolb, 2004). On the hand, parasol ganglion cells on the other hand receive input from parasol bipolar cells which typically have larger dendritic fields as well as RFs when compared to midget ganglion cells. Parasol ganglion cells are particularly sensitive to amacrine cells and as a result of this they receive a substantial amount of information from these cells, information particularly useful during scotopic conditions (McMahon, Packer, and Dacey, 2004).

2.5.1 Ganglion cell function type

As it is reported in the study conducted by Chichilnisky & Kalmar (2002) using multi-electrode recordings in non-human primates (i.e macaque monkeys), retinal ganglion cells, similar to bipolar cells, have two distinct regions - a central region (or ON centre region) and peripheral regions (OFF centre regions), which typically respond in an antagonist manner – opponency system, in the event when an illuminated stimulus being presented in a given area of the retinal ganglion cell’s RF. ON ganglion cells have a strong response rate (or firing rate) when luminous information is received on the centre of its RF and a weak response rate when luminous information is received on the peripheral (or surrounding) regions of its RF, OFF ganglion cells, on the other hand, have a strong firing rate when luminous information is received on the surrounding regions of its RF while a weak firing rate is typically observed when luminous information is received on the centre of its RF (see Figure 2.8 for a detailed illustration of how retinal ganglion cells typically respond to illuminated stimulus presented in different regions of its RF).

2.8: The Figure is unavailable due to copyright restrictions.

2.5.2 Ganglion opponency system

By applying this opponency system, typically observed in the retinal ganglion cell's RF (which is critical when visual information is received from a photoreceptor and when intermediate cells are being represented), it is also possible to work out how retinal ganglion cells process and represent information about colours with respect to a given object. There are three types of retinal ganglion cells involved in visual processing - parasol ganglion cells, midget ganglion cells, and small bistratified ganglion cells. Each cell type carries distinct information about a pair of opponent colours which is later sent through the Magnocellular, Parvocellular and Koniocellular pathways and projected into the Magnocellular, Parvocellular and Koniocellular layers of LGN (Dacey & Packer, 2003).

Parasol ganglions cells (or M cells) are responsible for processing and representing information about luminance which strongly corresponds to the black and white opponent colours (Gegenfurtner and Kiper, 2003). Because M cells, like all ganglion cells, process information sent from photoreceptor and intermediate cells in an opponent manner, ON centre M cells are typically excited when information, which contains the combination of L- and M- cones, is received by the centre of its RF. On the other hand, in the surrounding regions of its RF, information containing the combination of L- and M- cones is inhibited. OFF centre M cells react in the exact opposite manner: M cells are excited when the information is received by the surrounding regions of its RF and inhibited when information is received by the centre of its RF. Once information is processed and represented by a given M cell, this information is further separated and sent through the Magnocellular pathway which is later projected into the Magnocellular layer of the LGN (Wiesel and Hubel, 1966). On the other hand, Midget ganglion cells (or P cells) are responsible for processing and representing information about the red and green opponent colours. As it is noted in section 2.4, midget bipolar cells which evolved to receive a single input from cone photoreceptor cells, transmit information to P cells (see section 2.4.2). Because of this, ON centre P cells are excited by a single M- or L- cone input received by the centre region of its RF, while in its surrounding regions, input from a specific cone type, typically the opposite cone type of the one received by the centre region (e.g. M- or L-), is inhibited (Martin, Lee, White, Solomon, and Ruttiger, 2001). As it is expected, OFF centre P cells are also excited by a single M- or L- cone photoreceptor cell input. However, in this case, information received by the surrounding regions of its RF excites the cell, while the input from a specific cone types, typically the opposite cone types of the cone received by its surrounding regions, (e.g. M or L) received by the centre region of the cell's RF is inhibited. Information processed and represented by the RFs of the P cells is sent through the Parvocellular pathway, making up 80% of the retino-geniculate projections in GCL, and is eventually transmitted to the Parvocellular layer of the LGN (Gegenfurtner and Kiper, 2003).

The last retinal ganglion type cell discovered by Dacey and Lee (1994) are the small bistratified ganglion cells originally present in the ancient subsystems of primates which eventually accompanies a derived subsystem which includes P cells where red-green opponency is computed (Lee 2004). These cells contain colour information which is initially processed by S- cone photoreceptor cells and eventually transmitted to "blue-cone" bipolar cells (Dacey and Lee 1994). As a result of this, bistratified ganglion cells are typically known to be responsible for processing and representing information about the blue and yellow opponent colours. Unlike P and M cells, bistratified ganglion cells do not have a traditional (or classical) surround structure. As oppose to the classical OS found in P and M cell, OS of the bistratified ganglion cell is located exclusively in the centre region of its receptive filed (Hendry and Reid, 2000). As a result of this, most bistratified ganglion cells are often referred to as blue-ON bistratified ganglion cells. These ON bistratified ganglion cells are excited by inputs from S- cone photoreceptor cells which fall on the centre of the cell's RF, while OFF bistratified ganglion cells are excited by L- and M- cones, receiving their original input from horizontal cells (Dacey & Packer, 2003). Information processed by bistratified ganglion cells is later sent through Koniocellular pathways which project into the Koniocellular layer of the LGN (Hendry and Reid, 2000).

2.6 The relay centre of the visual brain

Most of what is typically understood as the human primate's conscious experience of colour, such as our day to day experience of colour or the recognition of an object's typical hue, is decoded and represented in the LGN. Although there are other retinal projections from retinal ganglion cells and other retinal cells in the heterocellular retina which project into the pretectum, superior colliculus and suprachiasmatic nucleus located in the thalamus, the LGN (or relay centre) is considered the main region in the thalamus where information processed in retinal ganglion cells is sent for additional processing and a detailed representation of the physical world (Mullen, Dumoulin, and Hess, 2008).

2.6.1 Sub cortical region: LGN

Colour information is projected in the LGN – a laminar structure in the thalamus composed of six main layers and additional interlayers. The two bottom (or deepest) layers in the LGN – layer 1 and layer 2 (i.e. Magnocellular layers) are particularly large (magno) in size due to their large nucleus (Teller, 2014). With respect to layers 3 to layer 6 (i.e. Parvocellular layers) cells generally observed in these layers are small in size. For example in a study conducted by Leventhal, Rodieck, and Dreher (1981) using retrograde tracers, a technique used to recover the cell group within a particular layer, they found that within the Magnocellular layers, cells usually displayed a large nucleus which habitually received input from M cells carrying information about luminance, while in the Parvocellular layers, cells generally had small nucleus responsible for processing information projected from the P cells which carried critical information about the red and green opponent colours. Following these studies, another study by Martin, White, Goodchild, Widler & Sefton (1997) using immunoreactive staining techniques in non- human primates (e.g. New World monkeys), underneath layers 1-6, Koniocellular layers (i.e. additional interlayers) were observed as cells within these layers, as Szmajda, Grunert, and Martin (2008) discovered, also using retrograde techniques, generally had smaller nucleus when compared to the P cells, which are responsible for receiving information from small bistratified ganglion cells carrying critical information about the blue and yellow opponent colours.

2.6.2 LGN's visuotopic map

Information transmitted from various retinal cells is represented onto six different visual (or visuotopic) maps each located within one of the layers, where an extremely magnified and detailed representation of the human primate's visual field is represented (Wandell & Winawer, 2011). In other words, visual information contained in the P cells, M cells, and small bistratified ganglion cells, initially processed and sent through three distinct pathways, is projected onto the LGN, stretched and spatially distributed within the maps of six different layers. For example when objects with certain visual properties (e.g. colour) in the physical world need to be represented, LGN maps are able to represent the different points of the visual field where the objects are being presented, providing the human primate with a detailed representation of these objects as well as the properties associated with them.

2.6.3 LGN colour opponency

The way colour information is processed and represented in the subcortical layers of the LGN can be understood through the opponency system typically observed in the retinal ganglion cells reviewed above. This opponency system was demonstrated in the study conducted by Krauskopf, Williams and Heeley (1982) which used psychophysical methods to measure whether the perceptual response of human primate to a targeted coloured stimulus would strengthen or weaken after being repeated presented with the stimulus' cardinal (or opponent) or non-opponent colours using the isoluminant DKL colour space . Results demonstrated that observers typically had a stronger perceptual response to the coloured stimulus if they were repeatedly presented the stimulus' opponent colour in the habituation stage of the experiment. Three different cardinal response pattern were discovered – red-green, blue-yellow and black-white, which not only corresponded with the cell type observed in the Parvocellular, Koniocellular, and Magnocellular layers of the LGN supported, but for the most part, the opponent process theory originally proposed by Hering (1920) (see Figure 2.9 for a simple illustration of the opponent process theory and how the opponent colours directly correspond to the Parvocellular, Koniocellular, and Magnocellular layers of the LGN).

The result from this study was also consistent with the previous neurophysiological study conducted by Wiesel and Hubel (1966) which demonstrated, by recording LGN cells in the Parvocellular and Magnocellular layers, that majority of the M cells in the Parvocellular layers were extremely sensitive to red-green opponent colours while P cells had a strong preference for luminance information. Moreover, a recent study on non-human primates macaque monkeys) conducted by Tailby, Solomon, & Lennie (2008) found that the cells in the Koniocellular layers typically have a strong preference for blue-yellow opponent pairs. Although colour information is processed and represented in the LGN layers, this information is further processed and represented in the primary visual cortex area of visual brain providing the human primate with an even more detailed representation of the physical world.

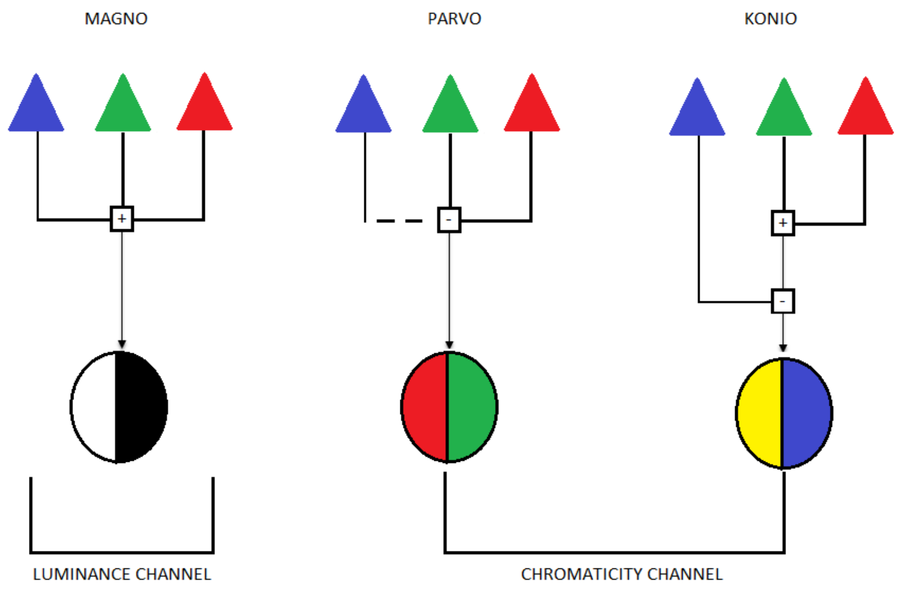


Figure 2.9: Illustration of the opponent process system originally proposed by Hering (1920) and supported by the way information is processed and represented in the LGN layers of the human primate. Starting from the left, P cells which are found in the Magnocellular layer of the LGN are colour blind and primarily responsible for processing and representing visual information about the motion and luminance in the human primate's visual field. The Parvocellular layers, which contain M cells, are primarily responsible for processing and representing the green and red opponent pair, while in the Koniocellular layer, bistratified cells are typically responsible for processing and representing the yellow and blue opponent pair in the visual field of the human primate. Because of this OS, it is impossible to experience the combinations of opponent colours (e.g. reddish-green or yellowish-blue), however, it is possible to experience the combination of orthogonal opponent pairs.

2.7 V1: main projection site

Based on empirical data from non-human primates (e.g. macaque monkeys), it is generally acknowledged that the primary visual cortex (V1) is the main projection site of the LGN. Thus, the information representing the human primate's visual field, carefully constructed in the Parvocellular, Magnocellular and Koniocellular layers of the LGN, is primarily sent through the optic radiation into V1 layers (Jeffries, Killian, and Pezaris, 2014). The cells responsible for transmitting this information are often referred to as relay cells – LGN cells which receive information from retinal ganglion cells, later sent to the higher cortical areas of the visual brain (see Figure 2.10 for a detailed illustration of the way information from the LGN layers are transmitted into V1 and the other cortical regions in the visual brain); 78% of the cells from the Koniocellular layer, 10% of the cells from the Parvocellular layer, and 12% of the cells from Magnocellular layer are relay cells (Szmajda, Grunert, and Martin, 2008). It is important to note that relay cells sent to V1 also feedback cells to the initial LGN layer, from where they were originally projected. Such feedback process allows V1 to emphasize visual information about the physical which need to be prioritized over against visual or colour information with less importance.

Figure 2.10: The Figure is unavailable due to copyright restrictions.

V1 is situated in the posterior region of the occipital cortex and is made up of six cortical layers. The layers in V1 are highly detailed, complex and above all assigned fixed and specific tasks, allowing the human visual system to process colour information and other visual infromation in the most efficient manner. The most dorsal layer in V1 - Layer 1 - is made up of axonal and dendritic spines projecting into the LGN and out of V1 into different areas of the cortex (Schmolesky, 2007). Because of this, Layer 1 is responsible for acting as a connection site, transferring information into different areas of the cortex, as well as providing feedback pathways when visual information needs to be projected back into the LGN. Apart from projecting into different cortical regions, this layer also receives a small amount of input from the Koniocellular layers in the LGN. V1 cortical area known as Layer 2 is assigned a task similar to layer 3A, that is, local processing – elaborating and refining the features that the given cortical area encodes. These levels have made up of cytochrome oxidase-rich blobs whose axons also seem to project into the higher cortical areas of the visual brain – V2, V3, V4, and MT (Schmolesky, 2007). In addition to this, they also receive small amounts of input from Koniocellular layers in the LGN. The fixed task of Layer 3B is to process and translate visual information projected into its layer from the Koniocellular layer of the LGN and subsequently transmit this information to V1 and extrastriate cortex (V2) and non-colour areas – middle temporal regions (MT).

The fourth cortical layer - Layer 4 - is arguable the most complex and important layer of V1. It is responsible for a number of basic day to day visual experiences (e.g. detecting the edges of objects in the physical world). This layer is arranged into the following sublayers - 4A, 4B, 4Cα, and 4Cβ. Layer 4A is morphologically similar to Layer 3B, it seems to serve as the gateway to the layers which make up Layer 4. It demarcates layers 3 from Layer 4 as dark band of granule- like cell are typically observed in this layer (Schmolesky, 2007). As Allman, Baker, Newsome and Petersen (1981) originally report, the task of Layer 4B seems to be the representation and translation of motion related information, later projected into the MT - an area containing Meynert cells, whose specific target is the MT. As a result, Layer 4B is particularly instrumental during motion processing. Cells within this layer are also transmitted into the Cytochrome Oxidase (CO) areas of the V2, while substantial amount of information processed in V2 is also eventually sent to the MT. The Layer 4Cα, as discussed by Kiper, Levitt, and Gegenfurtner (1999), is assigned the task of processing and further representing information projected from the Magnocellular layer of the LGN, responsible for processing and presenting luminance and motion-based information. Finally, 4Cβ is responsible for further processing and further representation information that is processed, represented, and transmitted from the Parvocellular layer of the LGN, primarily responsible for representing colour information about the red and green opponent pair.

What is particularly thought provoking about Layers 4Cα and 4Cβ is that, unlike the more dorsal layers in V1, which receive unintegrated input from the LGN, Layers 4Cα and 4Cβ receive input from different regions. It is also important to note that the sublayers of Layer 4 also send information to Layer 1 and 2 as well as to other areas in V1. As for layer 5 and 6 - although they layers receive a very small amount of information from different layers in V1, they have the important responsibility of sending feedback signals to Layers 2 and 1 - visual information which is eventually sent back into the LGN layers.

Deep layers of cortex also tend to have cells involved in long-distance connections (e.g. from cortical to subcortical areas, from one hemisphere to another, or from one cortical area to a distant cortical area).

2.7.1 V1: receptive fields and major cell type

With Layers 5 and 6 being for the most input-free, Layers 1, 2, 3, and 4 are the only ones receiving a significant amount of input from LGN layers, Layer 4, namely its sublayers 4Cα and 4Cβ, receiving majority of this input. The main reason why these layers are given such a high priority is simply due to the fact that they have centre-surround RFs similar to those observed in the LGN layers, making it extremely efficient to send inputs represented in the LGN layers into V1 area (Troncoso, Macknik, & Martinez-Conde, 2011). With this in mind, it is possible to focus only on the 4Cα and 4Cβ sublayers and thus investigate the type of visual information that is processed and represented exclusively within these two layers - as was done by David Hubel and Torsten Wiesel, the pioneers of modern vision research.

In the classical study conducted by Hubel & Wiesel (1962), researchers presented non luminous and luminous stimuli spatially orientated in different directions in the visual field of mammals (i.e. new born cats). During the presentation of each stimulus, an electrode was used to record the cells located in different layers of V1. Results demonstrated that a group of cells – simple cells – located in the 4Cα and 4Cβ sublayers (Yeh, Xing, Williams, and Shapley 2009) only responded to a given stimulus if it was presented in a certain direction and its spatial orientation was consistent with this direction. These cells also had a strong preference for stimuli with a certain width and contrast type (luminous or non-luminous). In other words, some cells within this layer only responded to stimulus vertically (or horizontally) presented and also vertically (or horizontally) spatially orientated. When the stimulus was presented vertically and spatially orientated in a non-vertical (or oblique) manner, excitation levels of these cells significantly decreased. Another group of cells was observed which not only preferred stimuli that were presented vertically as well as vertically spatially orientated but were of a certain contrast and width. When a given stimulus did not match these cells' preferred width or contrast, the cells' excitation level.

The cells observed within this same V1 layer are commonly referred to as complex cells (Hubel & Wiesel, 1962). Unlike the simple cells, these cells do not take into the account the location of the stimulus in the primate's visual field or whether the stimulus is of a particular contrast. The main concern of these cells is orientation and width of the given stimulus. In other words, whether a luminous or non-luminous stimulus of the same width is presented horizontally (or vertically) and also horizontally (or vertically) spatially orientated or not, the cells will respond in the same manner. It is only when stimulus' width and orientation shift that the cells' excitation levels substantially decreases. The last cell type, observed in this layer is commonly referred to as the end stop cells (hyper complex cells), originally discovered by Hubel & Wiesel (1962) and later rediscovered by Bolz & Gilbert (1986,). These cells are composed of both simple and complex cells and their excitation levels are particularly at their strongest when the stimulus increases in length - horizontally or vertically. When the stimulus is as long as the cell's RF or even longer, the cell's excitation is at its highest.

2.7.2 V1: colour-sensitive cells

A common observation about the cells located in V1 is that cells which prefer the same visual properties presented in the physical world are typically neighbouring cells and as result are grouped together within certain areas within the region. For example as discussed by Hubel & Wiesel (1968), when an electrode is inserted in V1 layers of non-human primates (i.e. macaque monkeys), either vertically or in an oblique manner, some cells in Layer 4 respond as a group. As a result of this, these cells form distinct columns, only responding as a group to a given stimulus of a particular orientation, excluding, cells in this layer who are insensitive to such information. Other groups of cells arranged into columns were also discussed by Hubel & Wiesel (1968,) while electrode recording in non-human primates, cells which have a strong preference for visual information received by the left or right eye. These cells are normally observed in the 4C layers of V1. However as it pertains to cells which have a strong preference for colour and thus may be useful during the processing and further representation of colour information in V1, these groups of cells may be contained in multiple areas.

In the classical study conducted by Livingstone & Hubel, (1984), researchers observed that there are in fact groups of colour-sensitive cells organized in and around the CO blobs, located between Layer 2 and 3 of V1. Information processed and represented by these cells is later transmitted to the CO stripes of the V2. This seems particularly intuitive as information from the Parvocellular and Koniocellular areas of the LGN is projected to these exact same V1 layers. Despite the major doubts this study gave rise to, a more recent study by Landisman and Ts'o (2001), using single- and multi-unit extracellular recording technique to record activity in non-human primates (i.e. macaque monkeys), found that colour-sensitive cells do in fact exist in groups. However, many of these colour- sensitive groups were located outside of Layer 2 and 3 of V1 and not between them, suggesting that colour-sensitive cells may be present throughout various area of V1 and not just in a single area, as was suggested in the study conducted by Livingston & Hubel, (1984). In light of this, the study conducted by Friedman, Zhou, and von der Heydt (2003), recording individual cells in V1 of macaque monkeys, observed that 64% of the neurons within the upper layers – Layer 2 and Layer 3 - were colour as well as edge-sensitive. A smaller population of colour sensitive cells was also discovered in the lower layers - Layer 4, Layers 5, Layers 6, while in the and V2 area, 45% of the cells recorded were observed as colour-sensitive cells. Unlike information about the orientation of objects in the physical world or ocular dominance columns, colour information seems to be processed and represented in different areas of V1. It also appears that the areas colour-sensitive cells are typically located in, is based upon the type of information (e.g. edge-sensitive) the particular colour information is being integrated with - as observed in the study conducted by Friedman, Zhou, and von der Heydt (2003). Nonetheless colour information processed and further represented in V1 layers is projected into the V2 area, from where the information is later projected into V4 area of the visual brain (Zeki, 1983).

2.8 V4: colour in translation

Although the role of the V2 area as it relates to colour processing is still debated, it is safe to conclude that to some degree, colour information is processed in the V2, noted in the study by Friedman, Zhou, and von der Heydt (2003). In an even more recent review by Sincich and Horton (2005), it has become increasingly clear that V1 and V2 layers are anatomically connected and that multiple layers in V1 project into the V2. This not only suggest that a substantial amount of colour information is projected into the V2, but that other types of visual properties – motion, depth, are sent to this area for further processing. Information leaving V1 eventually makes its way through either the dorsal (or parietal pathway) or ventral pathway (or temporal pathway), as it was originally discovered by Mishkin and Ungerleider (1982).

Much of the human primate's ability to experience the colour of familiar objects in the physical world is greatly indebted to V4. As a result of this, considerable damage in this region can, in certain conditions, lead to the inability to correctly perceive the colour of a given object. The complete damage in this region, which has been hypothesized to severely impair colour vison, is commonly referred to as cerebral achromatopsia (Zeki, 1990). In the classical study conducted by Zeki (1973), using single unit recording techniques on non-human primates (i.e. Rhesus macaque), Zeki discovered that almost all of the cells in V4 area were colour sensitive as they typically responded to the presentation of different colours of light and not to achromatic illuminants (Zeki, 1973). The study further noted that these cells were often observed to occupy different regions in V4 area and were not grouped together in a certain area of the region. As a result of this, this study concluded that V4 area was devoted exclusively to processing colour information about the physical world. Another study by Zeki (1983,), using psychophysical and single unit recording techniques on non-human primates, discovered that many of the cells in V1 were wavelength-sensitive cells, typically responding to different wavelength types (S- ,M-, L-), while cells in V4 area were colour-sensitive and responded to the actual colours of a physical object (Zeki 1983). When colours of the same wavelength type (e.g. orange and red) were presented, wavelengths-sensitive cells in V1 responded in the same manner, as they could not distinguish between the colours of the wavelengths. However, when the same stimulus was presented to the cells in V4 area, the colour-sensitive cells frequently responded in fundamentally different patterns. This lead to the conclusion that V1 is primarily responsible for processing wavelengths while V4 is responsible for translating wavelength information, allowing the human primate to understand, in the form of his or her day to day experience, colours in the physical world.

With growing doubt as to whether V4 area is of such great importance to the human primate's experience of colour, a very convincing study was conducted by Zeki, Watson, Lueck, Friston, Kennard and Frackowiak (1991) using Positron emission tomography (PET) to measure the following regions of interest (ROI) : V1, V2, V4, and the V5 of the human primate. When a moving black and white Mondrian patch was presented to the observers, significant levels of cortical activation were observed in V1, V2 and V5 area of the human primate. However, when observers were presented with static coloured Mondrian patches, the activation in the V5 considerably decreased, while V1, V2, and V4 area was significantly activated (Zeki, Watson, Lueck, Friston, Kennard and Frackowiak 1991). This study, as the first of its kind, not only suggested that V4 area is in fact a major colour region in the brain of the human primate, but that there is a strong anatomical connection between V1, V2, and V4, as well as between V1, V2 and V5, giving birth to the idea commonly known as parallel processing (for a complete review on parallel processing see Zeki, 1998). To get a more complete picture of V4's role in the human primate's day to day experience not just on colour but on familiar coloured objects - CDOs, another study by Zeki & Marini, (1998) using fMRI on human primates, was conducted. In this study observers were presented CDOs in their typical, atypical, and achromatic versions while the following regions of interests (RIO) - V1, V2, and V4 - were measured. The study observed that when achromatic versions of these objects were presented, only V1 and some parts of the V2 area were significantly activated. When observers were presented with the object in their typical hue, V1, V2, and V4 areas were significantly activated, whereas when observers were presented the incorrect atypical hue version (colours in which objects are rarely or never experienced in the physical world), activation in V4 area significantly decreased (Zeki & Marini, 1998). This led to the conclusion that V1 is primarily responsible for processing the wavelength of light associated with a given object, while V2 is responsible for refining the intensity associated with a given wavelength, leaving V4 primarily responsible for translating colour information associated with familiar objects that are often experienced in the physical world.

Figure 2.11: The Figure is unavailable due to copyright restrictions.

Despite the evidence which supports that V4 area is quite important to the human primate's experience of colour, the role of V4 area is still questioned by many. The lesion study on non-human primates, conducted by Heywood, Gadotti, and Coweyl (1992), found that despite the absence of V4 area, non-human primates' (i.e. Rhesus macaque) ability to discriminate between grey and a range of other coloured stimuli was roughly similar (Heywood, Gadotti, and Coweyl 1992). This result leads to the conclusion that V4 area may not be the only area responsible for colour processing. This also led to the idea that V4 area in non-human primates (e.g. macaque monkeys) may be anatomically different from V4 area of the human primate, further casting doubt as to the role of V4 area in the human primates' day to day experience of colour. In another study by Yasuda, Banno, and Komatsu (2010) recording the posterior inferotemporal (PIT) region using multicellular recording techniques in non-human primates, researchers found colour and shape selective cells in the PIT region (Yasuda, Banno, Komatsu, 2010). Such studies further suggest that colour translation may be occurring within various cortical regions, despite V4 area being the main area in which colour information is processed.

2.9 Chapter Summary

In this chapter a very brief review of the physiological layers in the heterocellular retina – ONL, INL, GCL , the sub-cortical region – LGN and the higher cortical regions –, V1, V2, V4,V5, collectively responsible for the human primate's initial experience of colour, was presented. Note that while there are other areas of the brain that respond to colour beyond V1, V2, V4 and PIT regions (e.g. medial temporal (MT) dorsolateral prefrontal cortex (DLPFC)) which allows the human primate's initial experience of colour a more adaptive value, this chapter simply aims to highlight how the human primate's initial experience of colour comes about and the patterns (or characteristics) that emerge from this initial process which may later influence top-down, cognitive processes (e.g. learning to form restricted object-colour associations). In light of this review, I would like to highlight two very important points. The first point is that however serendipitous it may appear, the human primate's experience of colour is only made possible because of a dedicated team of photons, retinal cells, sub cortical regions, and cortical regions of the visual brain, constantly processing and fine tuning colour information presented in the physical world. Without this dedicated team, the human primate’s experience of colour may not only be severely impaired, but in extreme conditions, completely absent (e.g. complete achromatopsia).

Secondly, the physiological areas involved in processing visual information about the physical world, namely colour information, while they are not assigned specific functions; they are primarily dedicated to a restricted range of tasks. For example, despite the different types of wavelengths present in the physical world, the cone photoreceptor cells evolved in such a manner in which they do not process or present information about light intensity outside of the bandwidth of the visible spectrum as their task is quite the opposite (i.e. restrictive) - process information about light intensity within a restricted bandwidth of the visible spectrum. The same is true for the cortical regions of the brain, as V4 area despite the different visual proprieties of a given object presented in the physical world, it evolved in such a manner that its task is to process information restricted to the surface information (e.g. colours) of a given object.

With these two points in mind, on one level it is quite fascinating that the human visual system undoubtedly enjoys consistency and in order to achieve this consistency the physiological areas it is composed of perform specific task as observed in the cone photoreceptor cells, intermediate cells, ganglion cells, LGN, V1, V2 and V4 regions of the visual brain. It should thus be of no surprise that some researchers suggest (e.g. Zeki, 2002) that the overall aim of the visual brain is to present the human primates with a fixed and constant representation of the physical world. It is thus further fascinating that not only are the physiological areas in the visual brain consistent in how they process, represent and translate colour in the physical world to the human primate, but also they deal with the inconstancy observed in the physical world. Take for example the problem of colour constancy and the V2 area estimating an illuminant's chromaticity a given object is illuminated under when presented in the physical world. Even though the illuminant's colour could considerably change the colour appearance of the object’s colour, this information is actively subtracted in the V2 area, allowing for its constant presentation. When the physiological areas, such as the V2 area, are unable to intervene and provide a consistent colour presentation of the objects in the physical world, the human primate seems to have its own ways of dealing with this problem, namely on the higher visual cognitive level. These mechanisms will be the focus of chapter 3.

3 Chapter 3

Organizing appearance into perception: psychophysical evidence for the role of colour name and colour knowledge

3.1 Introduction

The physical world is Heraclitian in nature – one which is not only abstract but always in a constant state of flux. As a result of this, the task of the visual brain is to acquire knowledge about the fixed and unchanging properties of the objects in the physical world in order to present the human observer with a more stable representation of it. This aim, as I have suggested in chapter 2, is achieved through various physiological mechanisms – bottom-up visual feature extraction, as in the case of colour constancy for example.

However, top-down, cognitive mechanisms also assist the visual brain in achieving this very aim. Note that, in this context, top-down cognitive mechanisms simply suggests that although the development of these mechanisms – language, strategic thinking (Gierer, 2004) - is not entirely dependent on the visual brain as much when compared to bottom-up visual feature extraction they are somehow influenced by it. As a result of this, these top-down, cognitive functions allow the human observer, for example, to create useful concepts such as colour names (or categories) (e.g. red, green, blue), colour related concepts (e.g. hue, saturation and brightness) as well as restricted object-colour associations with objects (yellow banana), whose colours' in the physical world, are actually presented inconsistently. As a result of this, the human observer is able to efficiently (not perfectly) organize, represent and understand the inconsistent appearance of a given object in a fixed and stable manner. In chapter 3, the concept commonly referred to as colour perception is defined and serves to illustrate its use in helping the human observer to organise, represent and understand the inconsistent appearance of a given colour presented in the physical world. Following the definition, the effects of colour category on colour perception is examined, highlighting influential theories - Relativist (or Sapir-Whorfian) and Universalist theory, primarily concerned with such area of research. A brief review of the studies which argues both for and against these two views is also provided. In the second half of this chapter, I explore the way a representation of an object's colour is formed as well as the nature of an object's memory colour in relation to CDOs.

Subsequently, the role of colour knowledge and memory colour[7] on the colour perception of CDOs is described in detail. This is done through an extensive review of previous psychophysical studies on CDOs. Towards the end of the chapter, the possible effects of the human observer's subjective experience on CDOs is introduced.

3.2 Hue, saturation and brightness

Photons (or light) at a given wavelength, eventually processed and represented in the physiological layers of the heterocellular retina, sub and higher cortical regions, can be psychophysically reproduced with light isolated and presented on a neutral (black or grey) background to a neutrally adapted eye using three variables. These three variables are commonly referred to as hue, saturation and brightness, while the combination of the three variables is commonly defined as colour perception (Burns & Shepp, 1988). In Figure 3.1, the three variables which help to organize the inconsistent appearance of a given colour perceptible to the human observer are highlighted. Hue is the first variable. This colour related concept corresponds to a given colour category which the human observer assigns to the colour appearance he or she judges to be presently perceiving. Note that as the wavelength, captured by the heterocellular retina and subsequently processed and represented in the sub and higher cortical regions change, the hue the human observer decides to associate with his or her ongoing perception is also likely to change. The second variable, saturation, refers to the degree to which a hue is mixed with white light. This colour related concept is in Figure 3.1 represented as the radii from the rim to the centre, which is assigned to the normal human observer's neutral point (see Figure 2.5). A highly saturated hue is most likely going to be located towards the centre of the colour space, while a less saturated hue is most likely going to be located closer to the rim. The third variable is lightness (or brightness) – a concept which concept corresponds to the human observer's ongoing judgement of the perceived intensity associated with a given hue. Brightness is represented in Figure 3.1 on the axis perpendicular to the hue-saturation plane. The brighter the hue the closer it is to the white pole, the darker the hue the closer it is to the black pole.

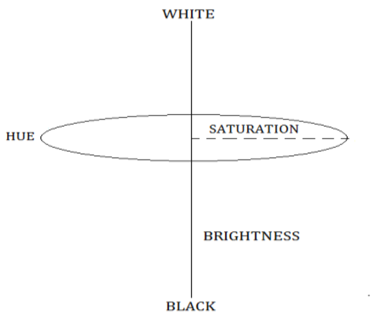


Figure 3.1: Illustration of the three variables which define a given colour perceptible by the human observers. The brightness axis is represented by the horizontal axis. The hue is represented around the circumference of the circle while the saturation is represented from the centre of the circle to its rim. Most colour spaces are navigable using these three variables (Munsell colour space), however, not all colour spaces and their variables are represented by the colour related concepts noted in this figure. Some colour spaces are modelled based upon the opponent process theory (L*a*b*

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[7] The term colour knowledge and memory colour are essentially top-down properties which make up the representation of a given object. However what makes them different is that while colour knowledge denotes information stored on the conceptual and lexical domain, memory colour denotes the information which is stored on the visual domain. Furthermore it is not a surprise that in some studies memory colour is also referred to as visual memory. This distinction will be further discussed in the following sections.

colour space), others are modelled based upon the different cone inputs in the LGN (DKL colour space). As a result, the concepts associated with their variables are going to be fundamentally different from the ones noted in this figure.

3.3 Influence of colour name on colour perception

Although it is possible to see how the colour related concepts, created by the human observer and illustrated in Figure 3.1 allow human observers a fixed and systematic way of organizing, representing and understanding the inconsistent appearance of almost any given colour or coloured object in the physical world, it is unclear how exactly these three variables are organized. In other words, what influences the organization of the final colour human observers decide to assign to a coloured object in the physical world? Over the past decade several hypotheses regarding the exact way human observers organize these three variables have been proposed. One of the most thought provoking hypothesis is the idea that colour categories (or names of hues) which are learned by human observers, influence, at some level, how the human observers organizes their ongoing perception of a given colour.

3.3.1 Relativist theory

The relativist theorists, led by linguists Edward Sapir and Benjamin Lee Whorf, argue that since the colour names assigned to a given appearance of colour vary from culture to culture and that the way we attempt to perceptually organize, represent and understand our appearance of a given colour is highly dependent on the colour categories we use, the human observer’s ongoing perception is inherently going to be influenced by them (Chatterjee, 1985). For example when a particular culture has various colour categories which do not include the colour category for the perception of a middle wavelength – green – human observers within that culture are less able to perceptually conclude that such an appearance is in fact green and will also struggle to discriminate between green colours and colours which are perceptually similar to it (e.g. bluish-green).

3.3.1.1 Evidence in support of the relativist model

The study conducted by Roberson, Davies and Davidoff (2002) offered the first clear evidence in support of the relativist model. In this study, Berinmo observers (tribal people of Papua New Guinea), who only have five basic colour categories – "wap" (light colours), "kel" (dark colours), “nol” (green and blue), "mehi” (pink, red and orange) and "wor" (orange, yellow, khaki, green and brown), were presented a Munsell chip of a given brightness and saturation value. There was a total of 160 Munsell chips presented to each observer which included the eleven basic colour categories observed among English speaking observers. During each Munsell presentation, the observer’s task was to perceptually organize each colour chip by assigning it a distinct colour category. Results demonstrated that Berinmo observers often had a difficult time correctly organizing hues which were not semantically represented in their culture, thus organizing them based upon how close they were to the colours semantically represented (see Figure 3.2 for the colour categories which are represented in the Berinmo culture when compared to English speaking observers). Bermino observers, for example, often organized green and yellow hues into the same colour category as these two hues were not perceptually distinct, while in the case of the English speaking observers who possess a wider range colour categories these two hues organized much differently. Results observed in this study led researchers to suggest the that way human observers organize the perception of a given colour is undoubtedly influenced by the colour categories which they use to organize these appearances - as in the case of Berinmo and English speaking observers.

Fig 3.2: The Figure is unavailable due to copyright restrictions.

Another recent study which provided further evidence for the relativist model was conducted by Winawer et al (2007). In this study, Russian observers, who had previously been observed to have twelve basic colour categories with the distinction between light - *sinij* and dark blue - *goluboj* colour category (Davies & Corbett, 1994), and non-Russian observers – English speaking observers with eleven basic colour categories, were individually presented blue coloured chips which fell within the Russian *sinij* or *goluboj* colour category. Towards the bottom of observers' visual field, another set of two coloured chips was later presented, from which the observers had to select as fast and accuracy as possible the coloured chip they judged to be the correct match for the blue coloured chip initially presented (see Figure 3.3 for an illustration of the stimulus presentation). Results demonstrated that Russian observers were much faster at selecting the correct coloured chip only when the pair of coloured chips they were forced to select from contained colours from both the sinij and goluboj colour categories. When the pair of coloured chips only contained colours from a single Russian colour category, response time was considerably higher for Russian observers. Such colour selection patterns were not observed for the non-Russian observers. Results observed in this study led researchers to conclude that cultures which have additional basic colour categories and as a result separate colours which are typically organized under one colour category will also have a discriminatory advantage, dependent upon the colour area the additional colour category is observed in. As a result of this, human observers in these cultures are able to better perceptually discriminate and organize better these colours when compared to human observers who do not have this additional basic colour category.

Figure 3.3: The Figure is unavailable due to copyright restrictions.

3.3.2 Universalist theory

Opposed to this position are the Universalist theorists led by anthropologists Brent Berlin and Paul Kay. Although these theorists agree that the appearance of colours is organized based upon various colour categories, they argue that the construction of these colour categories is not significantly influenced by a given culture. In fact, according to the Universalist theorists, these colour categories are fundamentally influenced by the way information about colour in the physical world is processed in the heterocellular retina in the sub and higher cortical regions of visual brain. For example, the RF of the Parvocellular layer of the LGN is one where the excitation of a colour red causes the inhibition of its opponent colour – green. As a result of this, the Universalists suggests that the visual brain already distinguishes between different primary and secondary colours categories, as observed in the LGN, and thus the sematic categories human observers develop are not dependent on their culture but fundamentally influenced by the physiological organization and processing of colour. The Universalists further argue that this is not only why we observe the absence of colour categories which are products of opponent combination – greenish-red or bluish-yellow - in the sematic categories of different cultures, but also why the 11 basic universal colour categories, which emerged in evolutionary stages, are largely composed of the primary and secondary colours or their combinations (Berlin & Kay, 1969).

3.3.2.1 Evidence in support of the Universalist model

The first study to provide compelling evidence for the Universalist model was conducted by Berlin and Kay (1969). Although ninety-eight languages were reported, only twenty of these languages were directly measured in two separate experiments, while the data for the other seventy-two languages were gathered from previous ethnographic data on colour names (see classic studies by Gleason, 1961 for more). As for the languages directly measured, in the first experiment, observers from twenty different cultures, each with different basic colour categories were individually presented a Munsell chip of a given brightness and saturation value. A total of 330 Munsell chips were presented to each observer. Observers' task was exactly the same as the one in Roberson, Davies and Davidoff study (2000) previously reported. It is worth noting however that, when performing this task observers were instructed to only select frequently used, mono-lexemic (e.g. red as oppose to light red) and non-contextual (e.g. Raphael blue) colour names (Berlin and Kay 1969). Results for this study demonstrated that observers, independent of their culture, often organized the Munsell coloured chips into under at least two colour categories and in the most extreme cases into eleven. Based upon this study, researchers concluded that all cultures generally have between two to eleven basic colour categories.

In the second experiment, observers' task was to perceptually define the outer boundary for each of the colour category defined in the first experiment and, using the Munsell coloured chips, to identify a prototypical colour they judged best represented each category. Results for this experiment demonstrated that boundaries for each colour category varied from culture to culture and did not reveal a clear universal pattern. However, as for the prototypical colours observers' were asked to select, researchers did in fact observe that observers' colour selections typically formed clutters on or around a single Munsell colour chip. Eleven Munsell coloured chips in total were identified to be corresponding to the frequently used colour categories in the English language excluding the following - royal blue, crimson and blonde (see Figure 3.4 for the eleven frequently used colour categories in the English language, and their associated evolutionary stages). This result led researchers to conclude that basic colour categories across cultures are all organized around universal focal colour categories that this is undoubtedly influenced by the way colour information is processed and organized in the heterocellular retina, sub and the higher cortical regions of visual brain.

Fig 3.4: The Figure is unavailable due to copyright restrictions.

Another study often perceived as additional evidence for the Universalist model was conducted by Regier, Kay and Cook (2004). Researchers in this study argued that since the observers used in the study conducted by Berlin and Kay (1969) were selected from industrialized countries, results may have been influenced by the nature of these countries and thus not a true representation of the basic colour categories across all cultures. As a result of this, data from the World Colour Survey (WCS) program were used, and, in the first experiment, observers from 110 non-industrialized cultures were presented a total of 300 Munsell coloured chips of a unique hue. Observers had the same exact task as in the Berlin and Kay (1969) study. Results confirmed the Berlin and Kay (1969) results previously reviewed as observers often organized the Munsell coloured chips around the first six universal basic colour categories – the Hering primaries. The black and white universal basic colour categories were the main colour categories observers used to organize a high percentage of the Munsell coloured chips presented (see Figure 3.5 for detailed results of Berlin and Kay study). In the second experiment, observers were asked to map out the colour boundaries for each basic colour category identified and select the Munsell coloured chip which they judged represented each of the basic colour category previously identified. Unlike the results noted in the Berlin and Kay (1969) study, results in this study demonstrated that although the colour chips selected were typically organized at the centre of the extended colour categories identified in the first experiment, the prototypical clusters across cultures did not fall exactly at the centre of each of the known basic universal colour category. Nevertheless, this study demonstrated that the basic colour categories across cultures are in fact organized around universally shared focal points, independent of whether that culture is industrialized or not.

Fig 3.5: The Figure is unavailable due to copyright restrictions.

3.4 Influence of familiar objects on colour perception

Exploring the effects of basic colour categories on colour perception is an important step towards understanding how the human observers organizes their initial appearance of a given colour. As I have demonstrated by reviewing these studies above, basic colour categories appear to have some influence on how human observers choose to organize the appearance of a given colour, especially if the colour is not semantically represented in that culture's basic colour categories - as was the case with Berinmo speaking observers or when the colour is represented in a much more complex manner within the basic colour categories, as was the case with Russian speaking observers. It also appears that, across cultures, the basic colour categories are organized around universal focal colour categories which provide the circumference within and around which a given culture's basic colour categories may later vary. However, the effect of basic colour categories on colour perception is just one of the top-down, cognitive mechanisms at work as human observers organize the appearance of a given colour. In other words, what about the role of objects in the physical world, particularly those which typically appear in a single hue and as a result are often mentally represented in a single prototypical colour independent of a given culture? Does these objects' colour knowledge (or memory colour) influence how the human observers choose to organize the appearances of these objects? Are there properties other than objects' colour knowledge or memory colour which influence how these objects are organized?

3.5 What is an object?

When we think of what an object is, whether it is familiar or not, we are essentially asking the following question: what are the information included in the representation of the object? Furthermore the representation of an object is tripartite – composed of three domains – visual, conceptual and lexical, while the information encoded in each domain has an intentional character – directed towards something other than itself (Brentano, 1924). With respect to the object's prototypical physical properties – shape, size, colour, texture, gloss, for example, which is included in the visual domain, this information has an intentional property; as it is about the object's physical properties and combinations of these properties which become important as the visual system attempts to recognize the object in question. The conceptual domain, the descriptive information encoded within this domain, which again has an intentional property, is about the human observer's conscious perceptual experience as relates to the object's physical properties, more specifically how constant the object's physical properties is in experience (e.g. does this object's shape or colour change when it is experienced in the physical world) (Collins and Quillian, 1969). As for the lexical domain, information included in this domain is typically about the object's lexical associations – how strong a given word is associated with a given object (e.g. foliage and green vs foliage and blue) (Meyer and Schvaneveldt 1971).

3.6 Object categorisation on familiarity

Keeping this definition of what defines an object, when referring to the term familiarity, this simply denotes an object which have a distinct category where information about that object is represented and most importantly not subjected to temporality and can in any condition be recovered and thus used to recognize, differentiate, and understand the object in typical and atypical presentations. Thus depending on the categorical theory one adopts, this will inherently determine the requirements an object must meet if it is to be designated as a familiar object.

Take for example the definitional theory on category. Theorist who adapt this position argues that in order for a given object to be designated a distinct category it must meet that category's definitional requirement. In other words if a given object is to be considered a member of a given category it must meet the “formal feature definition” which intrinsically defines that category (Wittgenstein, 1953). Information included in this definition affords the human observer general information which is used not only to identify a given object but further recognize the special features which distinguishes it from those within as well as outside of its category. For example based upon the formal feature definition of a fruit, that is, it generally has a restricted range of colours, has a stem and seeds are typically found on the inside - a banana would be considered a member of this category while a coconut would not. Such example should by itself raise some concerns as to the legitimacy of such an approach. Nonetheless, definitional theorists would designate an object as familiar if and only if that object has met the definitional requirement of that category and thus resembles other objects within the same category.

The second – exemplar theory - argues that in the physical world there exists a wide range of objects (or members) that generally fall into various but never a single category. Thus what ultimately forces a member into a single category is intrinsically phenomenological, that is, specific remembered experiences (or exemplars) stored in memory by the visual brain, in which newly presented members are compared to, in order to verify whether they belong to, or are representative of that particular category (Nosofsky, 1986). For example although a banana may be considered a member of the following categories: food, fruit, or the colour yellow, what determines its distinct category is its degree of similarity to the exemplars which currently make up. Thus if a banana is to be considered an object within the yellow category, its experienced features has to be similar to the exemplar objects which have already been stored in this category. While experience may play an important role in the categorization of various objects in the physical world it should be immediately clear that such a theory- exemplar theory may not be the most economical approach, particularly because of its reliance on experience which has an intrinsically indirect and ambiguous nature (Dennet, 1986). This approach eventually slows down observers’ ability to quickly make a judgement with respect to the object’s actual identity whenever it happens to be in question. Nonetheless the exemplar theorists would designate an object as familiar if and only if the object is frequently experienced in a way that the object matches the already experienced objects previously stored in memory.

The last group of theorists – prototypical theorists - contend that what actually determines a member’s natural category is the conceptual (Rosch, 1973; Storms et al, 2000). Thus if a given object is presented, by actively exploring the object rather than passively receiving information about the object, the observer is able to match the feature of the presented object to the features of the of the conceptual (or prototypical) object - an abstract average of the features of all the members within a given category. For example a banana may belong to the fruit category because its visual features strongly resembles the abstract average of the category’s prototypical object - an object that has a constant shape and colour conjunction, closely related object to hand size ratio, highly polished or containing coatings with finely dispersed pigments and has seeds on the inside. In light of this, the prototypical theorists would naturally designate an object as familiar if and only if the object’s features are close to the features of that category’s prototypical object. With this mind, we should immediately see from this approach that unlike the exemplar approach to categorization, the visual brain is able to quickly identify an object’s natural category which in turn allows the observer to quickly recover the identity of a given object. While prototypical theory is much more economical and appears to be the primary method the visual brain uses to categorize objects in the physical world, it does not explain non-prototypical category members – the incorrect classification of object. For example most observers typically classify cucumber – a fruit - as a vegetable. Thus if prototypical theory is in fact the primary method the visual brain uses to categorize a given object, which in some cases led to the misclassification of an object (e.g. fruit as a vegetable), there must be an secondary method it employs which later used to verify whether the members which has been initially assigned to a given category actual belong to the category. While there are those who argue that such verification process is done by exemplars, there may be a different explanation which will be discussed in chapter 5

3.7 Colour diagnostic objects

Colour diagnostic objects (CDOs) make up a subset of the familiar object population. According to Biederman and Ju (1988), in order for an object to be considered a CDO it must be perceptually experienced in the physical world in a single hue, which means that on the visual domain this frequency (or consistency) must be represented. As for the second requirement, the human observer must also have knowledge that the CDO has a typical hue which means that this knowledge must also be included on the conceptual and lexical domain along with other associated knowledge. Thus when the object's colour has to be recovered, the activation of this object's prototypical colour or colour term is typically experienced.

Take for example Figure 3.6 which illustrates two different CDOs. In almost any culture, Object A is perceptually experienced in a single hue and this known hue is represented on multiple levels. Thus it is no surprise that when human observers are instructed to recover this object's typical hue, the object's prototypical colour is automatically activated and the human observer is most likely to experience a colour sensation that closely resembles this object's prototypical colour and furthermore observers are able to recover the object's typical hue term with great ease. On the other hand, when the object is presented in an atypical hue, like in the case of Object B, human observers are also able to judge the colour presentation of the object as incorrect. It is worth noting that not all CDOs are natural objects and there are in fact many artificial objects typically considered as CDOs, such as the Object C. It is further worth noting that CDOs which have a typical hue whose colour presentation are not always in its typical hue are typically referred to as low colour diagnostic objects (LDO), while Object A and C are typically referred to as high Colour diagnostic objects (HDO).

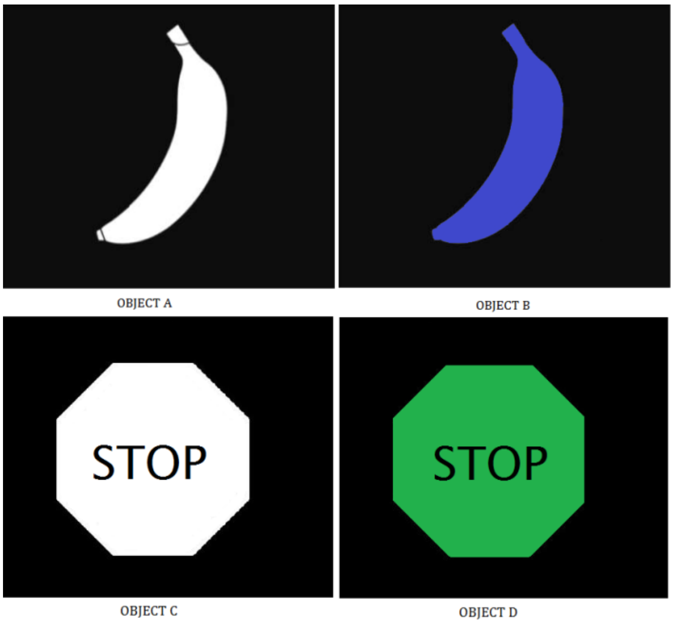

Fig 3.6: **CDOs in achromatic and typical hues.** Object A is banana and when asked to recover the hue they perceptually experience Object A in, most human observers would select a yellowish hue. Object B is a blue banana - which human primate known that the colour presentation of this object is atypical. When asked to recover the colour perceptually experienced in, most human observer would select a reddish hue. Object D is a green stop sign human observers know that the hue presentation of this object is atypical.

3.8 Traditional definition of colour knowledge

Knowing the typical hue a given CDO is typically presented in when experienced in the physical world, leads to the representation of this knowledge on the conceptual and lexical domain; the representation of this information is thus referred to as the object's colour knowledge (or world knowledge or object knowledge) (Mitterer and Ruiter, 2008; Witzel, Valkova, Hansen, and Gegenfurtner, 2011). Note, however, that the colour knowledge associated with a given CDO as it is currently defined, does not in the strictest sense, have to be consistent with the object's natural presentation in the physical world; a position this thesis disagrees with. In other words Object A, on its conceptual domain, may include the descriptors yellow and black spots and on the lexical domain, the colour yellow and the object's name may be closely linked together. However it is very clear that Object A is not only presented just in the colour yellow, therefore information included in this domain must somehow represent this reality.; this will be discussed extensively in section 3.13.

3.9 Traditional definition of memory colour

With respect to the object's visual domain, when the hue typically perceived in association with a given CDO in the physical world is stored and fixed in memory, such information is commonly referred to as the CDO's memory colour. At least in theory, it is thus impossible to have more than one memory colour for a given CDO, a position this thesis also disagree with. Nonetheless when the human observer is asked to recover the absolute (hue of a CDO, the automatic activation of the object's memory colour is typically observed which causes the observer to somehow overestimate the absolute hue of the object. This over estimation is referred to as memory colour effect (MCE) and is often dependent on the degree of naturalness associated with the presented object (Duncker, 1939; Olkkonen, Hansen and Gegenfurtner, 2008) (see Figure 3.7 for an example of the degree of naturalness associated with two CDOs).

3.10 Colour knowledge and memory colour interaction

The naturalness of a CDO is the amount of surface information (e.g. texture, gloss, and colour) present in a single presentation of an object, matching the object's physical presentation in the physical world to a high degree. When the human observer is instructed to recover the absolute hue of a CDO with a high degree of naturalness (i.e. including in its presentation the object's colour, gloss and texture which highly correspond to the object's physical presentation), the stored memory colour for this CDO is typically activated, prompting a strong MCE. If the CDO is low in naturalness, the activation of the memory colour associated with this CDO is substantially reduced, which causes the increase of conceptual and lexical information[8].

Figure 3.7: The Figure is unavailable due to copyright restrictions.

3.11 Literature review: the effect of colour knowledge and memory colour studies on colour perception

The earliest study to investigate the way colour knowledge and memory colour associated with a given CDO are used to organize the human observer's appearance of a given CDO was conducted by Duncker (1939). Eleven observers with normal colour vison participated in the study. In chamber 1, observers were presented either a leaf or a donkey with a low degree of naturalness, made from a green construction paper (see Figure 3.9 for an illustration of the experimental design). The green donkey and green leaf were presented under red illumination on a neutral background. The red illumination allowed each object an almost neutral appearance as the combination of any opponent pair (e.g. green and red or blue and yellow) produces a neutral hue. In chamber 2, observers were presented a colour wheel under normal (D65) illumination. During each trial, observer's task was to adjust the colours on the colour wheel to match the absolute hue of the targeted object presented in chamber 1. Observers were allowed to add or subtract green (greener), orange (browner), or white (lighter) hue, using the colour wheel. Results demonstrated that as for the leaf, 54% of the observers adjusted the leaf to a much greener hue (less saturated), 18% of the observers also adjusted the leaf to a greener hue, but not to the same degree, and as for 27% of the observers, there was no significant difference observed. The same colour setting patterns were not observed for the donkey (Duncker 1939) (see Figure 3.9 for complete result).

Figure 3.8: The Figure is unavailable due to copyright restrictions.

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[8] This argument is solely based on the physiological studies on memory colour and colour knowledge which are reviewed in the subsequent sections.

Before I discuss the implications of these results as it relates to the role of colour knowledge and memory colour on the colour perception of CDOs, several points about the experimental design must be noted. First and foremost, the stimuli used in the study had a low degree of naturalness as they were made from green construction paper. Secondly, colour settings were not directly made by the observers as each observer instructed the experimenter as to the direction they wanted to set the colour wheel, which may have influenced their colour setting.

With this in mind, this result could be interpreted in two ways. The first, a more conventional interpretation, is that colour setting of the green leaf was solely influenced by activation of the object's memory colour. As a result of this, for 18% of the observers activation of this object's memory colour was weak causing a weak MCE. For the 27% of the observers, the activation of the object's memory colour was even weaker as no MCE was observed. 54% of the observers demonstrated a significant MCE, with the object's memory colour strongly activated. Note however that this significant MCE may have appeared due to the fact that observers did not adjust the colour setting directly influencing the MCE observed. Because the degree of naturalness of the stimuli used in this study was extremely low, the second interpretation[9] which seems to be even stronger, suggests the effect observed is in fact not a MCE but an effect caused solely by the activation of the colour knowledge associated with the presented stimulus – leaf. In order for a true MCE to be observed, the absolute hue observers' select as the CDO's hue must be shifted towards a less saturated hue; the opposite was observed in this study. Thus, for the 54% of observers, their colour setting was actually influenced by the activation of the stimulus' colour knowledge (not memory colour). For the 18% of observers activation of the stimulus' colour knowledge was not as strong but present, while for the 27% of observers activation of the stimulus' colour knowledge was significantly weak. Nonetheless, results from this study led to the conclusion that the human observer's past experiences, which help us to form the memory colours associated with a given CDO as well as the representation of the object's prototypical colour somehow influences how human observers organize their ongoing colour perception of CDOs.

Figure 3.9: The Figure is unavailable due to copyright restrictions.

Following this study, a study was conducted by Bartleson (1960) exclusively aimed at investigating the role of colour knowledge on memory colour. In others words how does colour knowledge help in recovering the memory colour of a given CDO. Fifty observers with normal colour vison participated in this study and CDOs were verbally named to each observer. Additional facts about each object were given if observers requested them. Observer's task was to select a chip from 931 Munsell colour chips which they

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[9] Although the results yielded in this study are generally questioned by most researchers, this thesis is the first to interpret these results in an opponency manner.

judged to be the colour of the object previously named. Munsell coloured chips were all presented under 2,700 K illumination level (i.e. yellowish-white) on a neutral background, which illuminated the natural appearance of each coloured chip. The mean memory colour (MMC) for each object was computed by averaging the colour selection across all observers, while the mean physical colour (MPC) was computed by averaging the physical measurements for corresponding colour-diagnostic objects obtained from previous studies (Buck & Froehlich, 1948; Hendley & Hecth, 1949). Results demonstrated that colour knowledge incorrect recovered the wrong memory colour of r given object, creating a memory colour effect as observers often selected colours chips that were more saturated (opposite of the Duncker 1939) than the actual physical colour of the corresponding colour diagnostic object (see figure 1.20 for complete results).

By choosing to verbally name each CDO instead of presenting it, researchers were actively encouraging observers to rely exclusively on their memory colour retrieved from memory associated with the given CDO. Since there was no presentation to judge as an incorrect or correct colour presentation, observers' colour knowledge associated with the object was completely inhibited. However because this inhibition was caused by verbal presentation, we observe an opposite effect as that which was observed in the Duncker 1939. Also by asking observers to select from 931 Munsell patches, the researchers increased the likelihood for the observers to be possibly comparing colour patches as oppose to choosing a colour based upon the memory colour associated with that object. With this mind, this result can be interpreted in the following way: When the observers were instructed to select a colour chip, the memory colour of the CDO in question was automatically activated and influenced the colour chip observers selected, which was significantly different from the object's actual physical hue. By giving observers an infinite amount of time to select a colour chip, the researchers may have encouraged a greater reliance on the objects' memory colour or in fact caused observers to begin comparing colour patches among themselves, creating a bigger difference between MMC and MPC. In all, the results observed in this study led to the conclusion that colour knowledge included in the representation of a given CDO does in fact negatively influence visual memory, which is quite intuitive as visual memory, if it is to be as robust, requires the presentation of actual objects versus lexical presentations

3.10: The Figure is unavailable due to copyright restrictions.

What about the role of memory colour when CDOs of a high degree of naturalness are physically presented to the human observers? To answer this question, a study by Hansen, Olkkonen, Walter and Gegenfurtner (2006,) was conducted. Fourteen observers with normal colour vison participated in this study and were presented eight digitized photographs of natural fruit objects on a neutral background. A homogenously coloured disk and random noise disks with the amplitude spectrum of natural scene (1/f, pink noise) were used as control stimuli. In order to carefully separate the colour knowledge of CDOs from the memory colour of CDOs and directly measure the effect of memory colour on colour perception, observers had two tasks. In the first task, designed to encourage the activation of colour knowledge, observers had to judge the presentation of a non-prototypical CDO and adjust the object to its prototypical colour - not the memory colour. In the case of a banana, observers were presented a purple banana and instructed to judge the object and adjust the banana to its actual (not absolute) hue. In the second task, designed to encourage the activation of the object's memory colour, observers were presented a colour diagnostic object in its typical hue and asked to adjust the presented object until it appeared neutral – grey (a way of measuring its absolute hue). In the case of a banana, observers were presented a yellow banana and instructed to adjust the banana until it appeared grey. Observers adjusted the hue of the stimuli in the DKL isoluminant colour space, which the difference of L- cone minus M- cone represents the green and red opponent pair, while the L- cone plus M- cone minus S- cones, represents the blue and yellow opponent pair. The luminance (or lightness), represented by the L cone plus the M cone input, was kept constant (i.e. half of the recorded maximum monitor luminance) for the entire study (see Figure 3.11 for an illustration of the task observers had to perform). Observers were given an infinite amount of time during both tasks.

Figure 3.11: The Figure is unavailable due to copyright restrictions.

In the first task, a memory colour effect is impossible to be observed as observers were not instructed to retrieve their memory colour of the object. What should happen however is that observers should set each CDO to a hue which strongly corresponds to the object's actual hue. Furthermore, because the object representation of a CDO, which primarily includes its prototypical colour, is not as specific as the memory colour associated with a given CDO, observers setting in this condition should vary significantly. If there is no MCE, observers should set the hue of the presented stimulus (e.g. banana) to the physical achromatic point which should be the observer's grey reference point. In other words, colour settings should be roughly in the centre of the DKL colour space. If there is a MCE, observers should, set the hue of the presented stimulus (e.g. banana) away from the physical grey reference point in the opposite direction (i.e. opponent axis) of the stimulus' typical hue. In the case of a banana, despite being at the physical grey reference point, observers should still perceive some degree of yellowness in the banana and as a result of this overestimate its hue, similar to the observers in the Bartleson (1960) study.

Figure 3.12: The Figure is unavailable due to copyright restrictions.

Results demonstrated that, on average, observers selected in the typical colour setting, that is, in the first task, set each CDO to a hue which strongly corresponded to the object's actual colour. In the case of the banana (see Figure 3.12 for the complete results of this study), observers' colour settings often corresponded to a yellowish hue, corresponding to object's actual hue known to most of the observers.

However, as expected the hue selected by the observers varied significantly. For the achromatic (or neutral) colour setting, that is, the second task, observers' settings generally shifted away from the physical grey reference point in the opposite direction (i.e. opponent axis) of the stimuli's typical colour. No such effects were found for the control stimuli. In the case of a banana, once the observers reached the neutral point on the DKL space, they still perceived some of the yellow of the banana and in order to cancel this yellow, moved towards the opponent colour of yellow – blue, achieving a much more satisfactory neutral hue. This result led researchers to suggest that the memory colours of colour diagnostic objects are used by human observers to organize the colour appearance of these objects as they attempt to recover their absolute hue of a given object.

In light of the findings in the study by Olkkonen, Hansen, Walter and Gegenfurtner, (2006), Olkkonen, Hansen, and Gegenfurtner (2008) wanted to investigate whether the degree of naturalness associated with a given CDO would influence the degree to which a MCE is observed. Fifteen observers with normal colour vision participated in this study. Observers were presented eight different CDOs on a neutral background - either an original photograph of the object, a photograph of the object repainted in its typical colour, or a coloured outlined drawing of the object. A homogenously coloured disk and random noise disks with the amplitude spectrum of natural scene (1/f, pink noise) were used as the control stimuli. Observers had two tasks which were exactly the same as the tasks observers performed in the Hansen, Olkkonen and Gegenfurtner (2006) study.

Before the results and their implications are discussed, it is quite clear from the studies reviewed in this section thus far that CDO with a low degree of naturalness seems to either inhibit the presence of a MCE or weaken the observed MCE or in extreme cases a colour knowledge effect. When a CDO associated with a high degree of naturalness is presented, the object should yield a strong MCE. Results for this study are illustrated in Figure 3.13. As for the first task, which is not represented in this figure, results followed the exact same colour setting patterns as in the Olkkonen, Hansen and Gegenfurtner (2006) study. As for the second task, observers' settings generally shifted away from the physical grey reference point in the opposite direction (i.e. opponent axis) of the object's absolute hue. No such effect was found for the control objects. With respect to the CDO and their associated degree of naturalness, all of the original photographs of the objects – objects with highest degree of naturalness - yielded almost identical results as in the Hansen, Olkkonen and Gegenfurtner (2006) study. CDOs repainted in their actual hue demonstrated a slightly lower MCE. As for the outlined drawings of the CDOs, MCE was significantly lower as the presentation of these objects activated these objects' colour knowledge, which is not only symbiotic to the amount of surface information present when a CDO is presented, but fundamental in inhibiting the potential MCE. The results led researchers to conclude that the more surface information is included during the presentation of CDOs, the stronger the MCE observed.

Figure 3.13: The Figure is unavailable due to copyright restrictions.

Following the results demonstrated by the Olkkonen, Hansen and Gegenfurtner, (2008), study, Mitterer & Ruiter (2008) wanted to investigate the way colour knowledge associated with a given CDO, particularly the two CDOs which demonstrated the highest MCE - banana and orange, would influence how observers perceive a range of non-CDOs. Fifty-two observers with normal colour vision participated in this study. Observers were shown individual line drawings of CDOs in either their typical hues (e.g. yellowish) or their ambiguous typical hues (e.g. yellowish-orange). After each presentation, observers were individually presented, non-CDOs – the test objects - in the same exact hue as the CDOs initially presented. Observers' task was to indicate the actual colour of the test object by selecting a hue he or she believed corresponded with the non-CDO's actual (not absolute) hue.

Note that by initially presenting observers with CDOs associated with a low degree of naturalness, the observers were encouraged to activate the object's colour knowledge while reducing the activation of the object's memory colour. Observers' task to select the between two hues which restricted the observers' selection, again encouraged the activation of colour knowledge (remember that for the Bartleson 1960, study observers had the option of selecting from 931 Munsell chips as the researcher's aim was to obtain a much more specific hue (i.e. memory colour) associated with a given object). Because the CDOs in the study were always presented in the correct typical hue, one would expect the observers to typically judge the colour presentation of these objects as correct even if presented in an ambiguous typical hue. With these important points in mind, results demonstrated that, on average observers, selected incorrect hues for the non-CDOs whenever these objects were paired with a CDO. This same selection pattern was not observed for the control objects. In other words, whenever observers were presented with CDOs in a given hue, whether typical or ambiguous, the activation of the observers' colour knowledge (i.e. prototypical colour) was inevitable. As a result of this, observers, using the object representations of these objects, which primarily include these object's prototypical colour, often judged these CDOs as correct presentations. In doing so, they incorrectly perceived the non-CDOs, subsequently presented in the same colour. This result led researchers to suggest that the colour knowledge (or world knowledge) associated with a given CDO is not only restricting, as it only contains the object's prototypical colour, but also influential during the on-going perception of non-CDOs, whose actual hues, CDOs help to recalibrate.

Figure: 3.14: The Figure is unavailable due to copyright restrictions.

In the most recent study conducted by Witzel, Valkova, Hansen and Gegenfurtner (2011), researchers wanted to investigate whether an observed MCE is dependent not on the degree of naturalness associated with a given CDO, but on its type and hue type. Most of the types of CDOs experienced in the physical world are natural objects, such as a banana and a leaf. However, there are also CDOs experienced in the physical world which are in fact man-made (e.g. stop signs, McDonald logo, London telephone boxes). Most of CDOs are typically experienced in red, orange, yellow and green hues. However, there are CDOs which are sometimes experienced in blue, purple, pink and brown hues. Thus, will the MCE observed for CDOs which are experienced in different types of hues be significantly different from the CDOs typically experienced in the more traditional hues? In order to address these two questions, thirty -one observers with normal colour vison were, in a preliminary experiment, presented with range of man-made objects, typically experienced in a wide range of hues. A subset of these objects was selected as the CDOs researchers chose to measure in the main study. In the main study, observers were presented, on a neutral background in the DKL isoluminant space, seventeen man-made objects with a high degree of naturalness. A homogenously coloured disk and random noise disks with the amplitude spectrum of natural scene (1/f, pink noise) were used as control stimuli. Observers performed the same exact tasks as observers in the Hansen, Olkkonen, Walter and Gegenfurtner (2006) study and as in the Olkkonen, Hansen and Gegenfurtner (2008) study performed. The only modification in this study was the increase in the number of observers.

Figure 3.15: The Figure is unavailable due to copyright restrictions.

In Figure 3.15, results observed in this study are presented. In the typical colour setting, observers on average adjusted the hue of the object to the hue which corresponded with the object's actual hue. As expected the actual hues selected by the observers significantly varied, even to a greater degree, when compared to the results observed in the Hansen, Olkkonen, Walter and Gegenfurtner (2006) study, particularly for the blue and yellow man-made CDOs. This result suggests that for these objects' representation, unlike natural CDOs, knowledge other than these objects' prototypical colour may be included, affecting the actual hue observers typically selected. Results for the objects in the achromatic colour setting – activating the memory colour stored in memory - were consistent with the results observed in the Hansen, Olkkonen, Walter and Gegenfurtner (2006) study and in the Olkkonen, Hansen and Gegenfurtner (2008) study. In other words, observers' colour settings generally shifted away from the physical grey reference point in the opposite direction of the stimulus' typical hue (i.e. MCE). More importantly, this observed MCE was not dependent on the CDO type but on the hue type CDOs were typically experienced in when presented in the physical world. For CDOs typically experienced in a yellow or a blue hue, colour setting often fell along the daylight axis (more saturated colour setting) while the CDOs often experienced in red, green, purple and orange hues often demonstrated a much less statured colour setting.

This led researchers to conclude on three very important points. The first is that, for some human observers, depending on their individual experiences[10], the representation of a given CDO may include information other than the object's prototypical colours on multiple levels which may modulates the actual hue the observer recovers for a given object. The second point is that an observed MCE is not influenced by

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[10] Artificial objects are CDOs make up a higher percentage of the objects in most human observers' visual environment when compared to natural CDOs.

the CDO's type, but may be influenced by the hue type - as it was observed for the CDOs along the daylight axis. Finally because photopic vision occurs under daylight conditions which vary along the blue-yellow opponent axis (due to the combination of different amounts of direct yellow sunlight and bluish diffusion through Rayleigh scattering), the absolute hue of blue and yellow CDOs generally vary during the day, causing human observers to uncharacteristically overestimate these objects' hue shifting towards a less saturated hue and thus weakening the MCE.

3.12 Discounting the illuminant?

Keeping in mind the natural shift in illuminant, under natural daylight for example (see Figure 4.1 for an illustration of the variation of wavelengths observed under natural daylight condition) and the studies, which has been highlighted above, demonstrating the effects of colour knowledge and memory colour on colour perception, it is worth asking whether the colour knowledge or memory colour of a given object also aid the visual system as it calibrates small illuminant changes, discount the illuminant effect, and thus keep the observer's perception of a given object (e.g. banana) relatively constant?

In a recent study conducted by Granzier & Gegenfurtner (2012) this very question was investigated. In order to determine whether the presence of familiar objects, of which the reflectance is known to some degree, helps in estimating the illuminant's colour, observers in this study were presented three scenes containing seven objects; one scene with colour-diagnostics objects (e.g. yellow banana), another scene with incongruent colour of colour diagnostic objects (e.g. blue banana) and the last scene with 3-dimensional geometrical shaped figures (e.g. long curving cylinder). Depending on the trial, each scene included one of four matte coloured Munsell patches embedded exactly in the middle of the scene. This was referred to as the target unknown object. There were several illuminant conditions. Using the Munsell colour chart, observer's task was to match the surface of one of the four matte Munsell patches to the colour of one of the patches presented in the Munsell chart. Results demonstrated that observers were able to achieve higher colour constancy (i.e. select the correct Munsell patch regardless of the illuminant condition the Munsell patch was illuminated under) for the Munsell patches in the colour-diagnostic scenes with a 46.7% accuracy rate compared to 39% accuracy rate for the colour incongruent scene and 37.6% accuracy rate for the geometrical figured scene. The results suggest that when useful information is available, about a given object embedded within a given scene, the visual system will use this information as it attempts to discount the additional illuminant illuminating the presented object in order to keep the perception of a given object constant.

However CDOs do not make up a high percentage of the objects in our current environment, thus the visual system cannot reliance solely on such information in order to achieve colour constancy. Finally while a CDO maybe familiar, its constant shape and colour conjunction may not be a visual feature that as constant as previous studies suggest (see section 4.2 for more on the so-called constant shape and colour conjunction). Thus such inconstancy casts additional doubt on how reliable the use of memory colour or colour knowledge actual is as the visual brain attempts to discount the additional illuminant a given object is presented under in our day to day visual experience.

3.13 What about subjective experience?

Further considering the human observer's lived experiences (or subjective experiences) brings up a very interesting point which has been largely ignored though the colour perception literature. If the human observer's experiences under daylight conditions do in fact influence the absolute hue human observers assign a given CDO, what is the role of the human observer's subjective perceptual experiences in general, particularly when it comes to the colour knowledge? What about CDOs whose perceptual changes do not stem from the daylight illuminant but are somehow central to the object's natural colour presentation, typically observed during the primate's daytime experiences with these objects? If human observers daytime experiences influence the memory colour associated with a given CDO, should this daytime experience not influence also the colour knowledge and hence the representation of the object? Addressing these questions will be the aim of Chapter 4, in which the overall aim and the methodology used in this of this thesis will be provided.

3.14 Chapter summary

In this Chapter, I demonstrated that the primordial aim of the visual brain is not exclusively achieved through the fixed and stable processing of visual information, namely colour information, in the heterocellular retina sub and higher cortical regions but also through the development of colour concepts colour categories, object-colour associations which help to create a fairly stable representation of the physical world as it is the case with CDOs. I also reviewed studies which explored the different phenomena which emerges, due to the development of colour concepts, colour categories and object associations, causing the human observers to either lose or gain the ability to perceive the differences between certain categories of colours, or providing him or her useful information which can later be stored in the representation of the object – CDOs. Finally I explored the role of the colour knowledge and memory colour associated with a given CDO on the human observer's ability to recover these absolute hues. In the next chapter, the first experimental chapter, I will discuss the overall aim of this thesis and provide the techniques and methods used to design the experiments reported in this thesis.

4 Chapter 4

General Methods

4.1 Introduction

In this chapter, the overall aim of this thesis and its theoretical justification is presented. Following this presentation, the techniques and methods used to design the two main experiments, which are reported in this thesis, are explained in great detail. This is done by providing a theoretical introduction to gamma correction, followed by the techniques used to calibrate the computer monitor used in these experiments. Next, a theoretical introduction to colour space is provided, explaining why the CIE L*A*B* colour space was selected as the colour space for each experiment. Following this, a theoretical justification as to why the stimuli used in these experiments were selected is presented, along with the description of how they were generated. Towards the end of this chapter, the first experiment, which allowed for the empirical selection of the final stimuli used in the second experiment (main experiment), is presented.

4.2 Overall aim of this thesis

As it is noted in the study conducted by Witzel, Valkova, Hansen and Gegenfurtner (2011), the human primate's day to day experience of CDOs, namely the perceptual experience of yellow and blue CDOs, significantly vary. This variation is largely due to the fact that yellow and blue CDOs are typically experienced under natural daylight which contains in the morning mostly short wavelengths of light and slowly shifts towards long wavelengths of light as the day progresses (Brainard, 2002). As a result of this, a yellow banana, for example, typically appears in the morning under normal conditions slightly greyish (less saturated), due to its presentation under shorter wavelengths of light. As the day progresses, the object is presented under longer wavelengths of light, allowing a more typical (more saturated) colour appearance. When the human primate has to recover the absolute hue of a banana, his or her memory colour, as it has been demonstrated in the studies reviewed in section 3.8, causes the human primate to overestimate the absolute hue of the banana towards a more bluish hue (GRAY) which undoubtedly reflects the observer's day to day perceptual experience with the banana.

4.1: The Figure is unavailable due to copyright restrictions.

Despite the fact that the colour presentations of CDOs vary throughout the course of the day, the variation of a given CDO's colour is not exclusively due to the variation of natural daylight; it can also be attributed to the object's natural colour. A banana, for example, is typically experienced, under normal daylight conditions, in a hue which corresponds to the colour yellow and during the day vary within this hue. However, under normal daylight conditions, it is also possible for a given banana to be perceptually experienced in a hue which corresponds to the colour green and even in some cases dark brown and red[11]. In these conditions, the banana's change in hue does not by any means occur due to the variation of

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[11] **In Costa Rica and in Nicaragua, for example, bananas are commonly experienced in a reddish hue. These bananas are commonly referred to as 'banano caribe'.**

wavelengths observed under natural daylight but due to the fact that bananas are sometime presented in these atypical hues. Surprisingly, this phenomenon is often deemed as irrelevant and has been thus completely dismissed in all of the studies concerned with the physical and object representation of CDOs.

If the physical representation, that is, the memory colour human primates form and maintain in memory for a given CDO, is influenced by the human primate's experiences with these objects under natural daylight conditions, these objects' mental representation should also be influenced by the human primate's experiences, especially when these objects are frequently experienced. In other words, for certain groups of CDOs, the single typical hue which these objects are experienced in is known and thus is immediately included in these objects' representation. There are, however, groups of CDOs frequently experienced in more than one hue which are also known by the human primate. Thus, it seems quite clear that since human primate has knowledge of these hues, these objects' representation should also include the prototypical representation of these additional hues. To test this hypothesize is the overall aim of this thesis.

To accomplish this aim, two experiments were conducted. In the first experiment, the colour diagnosticity of potential CDOs was measured using a colour decision-time task. After identifying the objects with high colour diagnosticity, an experiential rating task was used to explore whether any of these objects constitute a high percentage of the objects which make up a given observer's normal day to day visual environment. With the identification of CDOs frequently experienced - FECDOs, the atypical hue in which these objects are commonly experienced and which is commonly known by most human primates, thus referred to in this thesis as these objects' CNP, was used in the main study to directly investigate how this knowledge influences the human primate's ability to recover these objects' prototypical colour and prototypical colour category. However, before the specifics of these experiments are expounded upon, the techniques and methods used to design these experiments must be presented.

4.3 Brief introduction to gamma correction

In colour vision research, it is universally understood that in order to display the correct electron-beam current (or intensity of light) for a given image displayed on a physical device (e.g. computer monitor), the physical device being used to display that particular image must be linearized - its gamma must be corrected. The reason for this is quite simple. The intensity of light generated by a physical device requires three digital values – red, green and blue - which are assigned a corresponding video voltage value raised to a given exponential value. This exponential value is commonly referred to as the gamma. By obtaining the gamma associated with each digital value and their corresponding video voltage value, it is possible to linearize the video voltage value and thus the presentation of the image.

For example, in a computer monitor similar to the one used in the experiments conducted in this thesis, each video voltage value has a corresponding electron gun which later excites the three primary phosphors. When luminous information is being sent from the video voltage to the electron guns, carrying information about the intensity of light to display, this information is sent in a non-linear fashion. As a result of this, the intensity of light illuminated from the computer monitor is incorrect. The relationship between the emitted intensity of light and the video voltage along with its associated primary phosphor is described in the Equation 4.2 (Taylor, 1994), where L is the luminance intensity of light, which is typically measured in cd/m^2, V denotes the video voltage value, while γ is the exponent (or gamma) associated with the video voltage and k denotes each primary phosphor - R' G' B' channels (or the red, green and blue channel).

$$L = V^{\gamma k} \quad \text{, where } 0 < L < 1 \tag{4.2}$$

4.3.1 Apparatus & Gamma correction

As for the computer monitor used in the experiments reported in this thesis, the following methods and techniques were used in order to linearize the electron-beam current – luminous intensity of a Dell 2407WFP monitor powered by NVIDIA GeForce GTX 650 graphics card with a spatial resolution of 1152 x 864 pixels and a refresh rate of 60 Hz. First and foremost, the brightness and contrast control on the monitor was set, following the exact steps specified in a short review by Poynton (200). Next, squared colour patches subtended 32.7 deg x 24.3 deg visual angle, representing each primary phosphor channel - R' G' B' , were created using the *"Fill Rect"* function in MatLab with the Psychophysics toolbox-3 extension (Brainard; 1997; Pelli, 1997; Kleiner et al, 2007). For each primary phosphor channel a total of 14 patches were created, at a constant interval ranging from 0 to the highest voltage - 255. Shortly after the squared colour patches were created, in a completely dark room, the luminous intensity of the video voltage associated with each of the 14 patches which make up a single phosphor channel was measured in cd/m^2, using a LS-100 luminance meter. A total of 32 measurements were recorded.

Following this, a 3 by 14 matrix which contained the 32 luminance measurements was later inserted into an in-house gamma correction function written in MatLab with the Psychophysics toolbox-3 extension (Brainard; 1997; Pelli, 1997; Kleiner et al, 2007). This MatLab function was designed to calculate the gamma associated with each phosphor channel - $R^{\gamma}, G^{\gamma}, B^{\gamma}$. After the corrected gamma was obtained, each gamma (or exponent) was applied to each phosphor channel which linearized the presentation of each stimulus before its final presentation[12] on the computer monitor. This exact same gamma correction methods and techniques were periodically performed in the beginning of each of the 8 testing days (see Figure 4.3 for the gamma obtained for the entire testing period). Finally the background of the computer monitor was always set to a black hue with a luminance value of 23 cd/m^2.

Testing day	R^{γ}	G^{γ}	B^{γ}
1	0.3710	0.3715	0.3901
2	0.3710	0.3715	0. 3901
3	0.3708	0.3713	0.3901
4	0.3710	0.3713	0.3901
5	0.3709	0.3713	0.3901
6	0.3710	0.3715	0.3901
7	0.3710	0.3715	0.3901

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[12] im_gamma = uint8(255/2*apply_gamma_correction(Rexp,Gexp,Bexp,double(CDO));

8	0.3710	0.3715	0.3901

Tale 6.1: Gamma obtained at the beginning of each testing day. Note that a given video voltage and each of its associated phosphor channels along with the luminance were normalised between the values of 0 and 1. As a result, gamma was never less than 0 or greater than 1.

4.4 Brief introduction to colour spaces

Equally as important as the calibrated monitor is the colour space. In the strictest sense, colour spaces are mathematical representations of a wide range of colours which allows the human primate to organize, represent and visualize a given colour. The colour gamut – the circumference of a given colour space, is for the most part navigable with three co-coordinates which represent the three variables of a given colour which may or may not be perceptible to the eye of the human primate. Each coordinate can be adjusted independently or in combination with other coordinates on a given colour space. Because there are various types of colour spaces designed to organize, represent and visualize a wide range of colours in their own unique way, what exactly the co-coordinates of a given colour space represent is entirely dependent upon the theoretical framework the colour space is modelled within.

Most colour spaces are either device dependent or independent of a given device (Ford and Robert, 1998). When a colour is organised and represented within a given colour space, it is possible for the human primate to visualize it, assuming that the human primate has a normal colour vison and that the physical device the object is presented on has been recalibrated (gamma has been corrected). Let us, however, assume that the same exact colour is organized and represented in the same colour space but presented on a completely different physical device and the same observer thus happens to perceive this colour differently. In this case, the perception of the colour, organized and represented in the same exact colour space, is not entirely dependent on the colour space but on the physical device used to present the colour - the colour space is device dependent. On the other hand, for colour spaces which are device independent, the observer's perception of a given colour is entirely dependent on the colour space as it does not change from device to device.

It is further worth noting that for any given colour related experiment, it is not only important to consider whether the colour space is device dependent or independent, or what theoretical framework serves as the model for designing the colour space, but also whether the colour space is able to measure in the most efficient manner the phenomenon the experiment seeks to investigate.

4.4.1 RGB colour space

In colour related experiments, one of the most widely used colour spaces is the RGB colour space. This colour space was modelled after the trichromatic theory which was proposed by Young and Helmholtz (1802). Although this theory does not explain the way colour is processed in the heterocellular retina and the higher cortical regions of the visual brain completely, the theory suggests that three cone photoreceptor cells which strongly correspond to the colours red, green and blue, are solely responsible for colour processing. As a result of this, the RGB colour space is an additive colour space. By combining the three coordinates which represents the colours red, green and blue - used to form a given colour - it is possible to organize, represent and visualize most of the colours perceivable by human primate. The relationship between R'G'B' values and the colour produced is described in the Equation 4.4 (Fairchild, 2005), where rR' with a maximum value of 255 is the amount of red contained in C, gG' with a maximum value of 255 is the amount of green contained in C and bB' with a maximum value of 255 is the amount of blue contained in C, while C is the colour produced when a given amount of all three values is combined. For example when C equals brown, rR' typically equals 165, gG' equals 42, and bB' equals 42 respectively.

$$C = rR' + gG' + bB' \tag{4.4}$$

As previously noted, the RGB colour space is theoretically flawed as the HVS is not entirely based on the three cone photoreceptor cells but on an OS typically observed in the retinal ganglion cells of V1. As a result of this, RGB colour space is non-linear to HVS as there is in fact a range of colours perceptible by the human primate, not represented in this colour space. In addition to this, the RGB colour space is also device dependent.

4.4.2 CMY (K) colour space

Another type of colour space commonly used within the field of colour vision is the subtractive colour space. CMY (K) colour space is a classic example of such colour space. Within this colour space, there are three co-coordinates which represent the three variables that make up a given colour. The first coordinate is C (or cyan) which denotes the equal combination of the G and B primary observed in the RGB colour space. The second coordinate is M (or magenta) which denotes the equal combination of the R and B primary, while the third coordinate - Y (or yellow) denotes the equal combination of the R and G primary. The combination of C, M and Y produces K which represents a black hue. The theoretical basis of this colour space is that by subtracting from a given lightness value - typically the human primate's perceptual response to a D65 illuminant (e.g. white light) – it is possible to produce a wider range of colours perceivable by the eye of the human primate than within the RGB colour space. As a result of this, by adding one of the three variables - C, M, or Y to a white background, this subtracts the amount of light perceived by the human primate, eventually producing not only denser colours but a wider range, reflecting the HVS much better. Because the RGB colour space and the CMY (K) colour space have similar computational basis, the linear transformation between the two colour spaces is fairly straight forward and described in Equation 4.5 (Ford and Robert, 1998, p.12). In the left matrices, it is possible to work out the corresponding CMY (K) of any given RGB value by subtracting the value of the given R, G, B primary from 1, representing a white hue in the CMY (K) colour space. In the right matrices, it is also possible to work out the corresponding RGB values of any given CMY (K) values by subtracting the value of C, M and Y from 1, representing a black hue in the RGB colour space. Despite the noted perceptual improvement of the CMY (K) colour space, the space is also not linear with the human primate's perceptual system and is also device dependent.

$$\begin{bmatrix} C & & 1 & & R \\ M & = & 1 & - & G \\ Y & & 1 & & B \end{bmatrix} \quad \begin{bmatrix} R & & 1 & & C \\ G & = & 1 & - & M \\ B & & 1 & & Y \end{bmatrix} \tag{4.5}$$

4.4.3 HSL colour space

The HSL colour space and the colour spaces similar to it – HCI, HIS - make up another group of colour spaces frequently used in most of the earlier colour related studies (e.g. Duncker, 1939, Bartleson, 1960). Although this colour space is for the most part computationally based on the RGB colour space, its theoretical basis corresponds, on the most basic level, to the way colour information is processed in the heterocellular retina and higher cortical regions of the visual brain. As noted in chapter 2, when light is captured by the human eye and immediately processed in retinal cells and higher cortical regions, luminance and chromatic information not only travels through different pathways but is processed in different areas. In light of this, the HSL colour space is among the first colour spaces to represent the luminance and the chromaticity of a given colour on separate axes. The first coordinate in the colour space is denoted with an H, representing the hue associated with a given colour. The second coordinate is denoted with an S, representing the saturation of the colour. These two axes make up the chromaticity of a given colour. The third coordinate – L - represents the luminance of the colour (or its intensity value). The relationship between R'G'B' values and H'S'L' values is described in the Equation 4.6 to 4.14, developed by Travis (1991). S is obtained by taking the min of a given RGB value (lowest RGB value) and subtracting it from the max of the same RGB value (highest RGB value), divided by the max. V is simply the max of the RGB value divided by 1. The hue, H, is obtained by first working out whether the RGB value is achromatic or not. In Equation 4.8, each R' G' B' value is divided by the difference between the max and the min of the RGB values. When S is 0, the hue for that particular RGB value is undefined – achromatic. In the case when S is not zero, H can be obtained using Equations 4.9 to 4.14.

$$\frac{(\max-\min)}{\max} = S \tag{4.6}$$

$$\frac{\max}{1} = V \tag{4.7}$$

$$\begin{gathered}\frac{\max-R}{\max-\min} = R' \\ \frac{\max-G}{\max-\min} = G' \\ \frac{\max-B}{\max-\min} = B'\end{gathered} \tag{4.8}$$

then, if R = max and G = min

$$5 + B' = H \tag{4.9}$$

else, if R = max and G $\neq$ min

$$1 - G' = H \tag{4.10}$$

else, if G = max and B = min

$$R' + 1 = H \tag{4.11}$$

else, if G = max and B ≠ min

$$3 - B' = H \tag{4.12}$$

else, if R = max

$$3 + G' = H \tag{4.13}$$

otherwise

$$5 - R' = H \tag{4.14}$$

4.4.4 CIE xyY colour space.

The last colour space reviewed in this section is the CIE L*a*b* colour space which is for the most part modelled after the CIE 1931 XYZ colour space. As it is noted in chapter 2, the L- , M-, and S- cone photoreceptor cells are sensitive to different wavelengths of light. The L- cone photoreceptor cells are most sensitive to longer wavelengths of light which typically, but not always, correspond to the colour red. The M- cone photoreceptor cells are most sensitive to middle wavelengths of light which typically, but not always, correspond to the colour green. The S- cone photoreceptor cells are mostly sensitive to smaller wavelengths of light, most of times corresponding to the colour blue. Keeping this in mind, it is possible to create three stimuli modelled after the typical colour responses of each cone photoreceptor cell observed in the heterocellular retina of the human primate, which is exactly what was done during the CIE's studies on human primates. With each tri-stimulus values – X, Y, Z, representing the amount of red, green and blue wavelengths of light most likely to be captured by each cone photoreceptor cell of the human primate, it is possible to combine a certain amount of red, green and blue wavelengths of light and thus mathematically record the human primate's perceptual response to that combination of light.

Using this as its mathematical basis, the CIE xyY colour space was created. In Equation 4.15 to 4.16 (Fairchild, 2005), the relationship between each tri-stimulus value and the way a given colour is defined in the CIE xyY colour space is described, where the tri-stimulus values X and Y are divided by the sum of the tri-stimulus values. This eventually gives us the value of Yxy - the defined hue at a given luminance value. Note that the tri-stimulus value Y, which corresponds to the M- cone photoreceptor cells and which was used to represent the luminance of any given hue defined in this colour space as green wavelengths of light often has a higher lightness value than blue and red wavelengths of light of an equal intensity. Moreover, the x and y values (or chromaticity values) can be visualized using the CIE x-y chromaticity diagram illustrated in Figure 4.17. Although the CIE XYZ 1931 colour space is perceptually linear to the HVS, separates the luminance information from chromatic information and is device independent, certain hues (e.g. green and purple) are difficult to discriminate from each other along certain axes (e.g. yellow and blue axis).

$$\mathrm{x} = \frac{\mathrm{X}}{\mathrm{X+Y+Z}} \tag{4.15}$$

$$\mathrm{y} = \frac{\mathrm{Y}}{\mathrm{X+Y+Z}} \tag{4.16}$$

Figure 4.17: The Figure is unavailable due to copyright restrictions.

4.4.5 CIE L*a*b* colour space

Using the CIE xyY colour space model as its mathematical basis, the CIE L*a*b* colour space was created in order to make the hues, which were originally difficult to perceptually discriminate from each other, easier to distinguish, using the opponent process theory as its theoretical foundation. In the L*a*b* colour space, there are three variables which can be specified for a given colour. L* denotes the degree of lightness associated with a given colour, a* denotes the red-green opponent channel observed in the Parvocellular layers of the LGN, while b* denotes the yellow-blue opponent channel observed in the Koniocellular layers of the LGN. Equation 4.17- 4.19 (Fairchild, 2005) describes the relationship between the L*, a*, b* coordinates and the XYZ tri-stimulus values and how for any XYZ tri-stimulus values their L*a*b* equivalent can be obtained. In Equation 4.17, L* is obtained by taking the f (or function) of Y for a given colour divided by Y_n which denotes the Y's reference white point - point on the colour space where the colour white is defined. Note that the L* axis is normalized between 0 (black) to 100 (white), as the L* value typically falls within this range. As for opponent parameters in Equation 4.18, a* is obtained by taking the X (red) value and its reference white point value and subtracting it from the Y (green) value and its white reference point. The sum of this is finally multiplied by a constant – 500, as the values within this b* axis fall, when computed, within the -128 to +127 range. In Equation 4.19, b* is obtained by finding the Y (green) value and its white reference point and subtracting it from the Z (blue) value and its white reference point. The sum is later multiplied by the constant – 200; similar to the a* axis, this axis is also scaled from -128 to +127.

$$\mathrm{L}* = 116 f\left(\frac{y}{y_n}\right) - 16 \tag{4.17}$$

$$\mathrm{a}* = 500\ [f\left(\frac{x}{x_n}\right) - f\left(\frac{y}{y_n}\right)] \tag{4.18}$$

$$\mathrm{b}* = 200\ [f\left(\frac{y}{y_n}\right) - f\left(\frac{z}{z_n}\right)] \tag{4.19}$$

Because X/Xn, Y/Yn, and Z/Zn usually produce, when computed, values greater than 0.01, in the rare case when the tri- stimulus values falls below 0.01, Equation 4.20 proposed by Pauli (1976) is often used. *f*(x) which represents the slope of a given L*a*b* value is separated into two parts in order to control for an infinite slope when x = < 0.01, where *f*(x) is linear below a given x $=x_0$ and thus equates to $x^{1/3}$ at x_0 in slope and value.

$$f(x) = \begin{cases} x^{\frac{1}{3}} & if\ t < 0.008856 \\ 7.787x + \left(\frac{16}{116}\right) & if\ \mathrm{t} \geq 0.008856 \end{cases} \qquad (4.20)$$

Keeping in mind that the CIE L*a*b colour space is linear to the HVS, device independent, separates the chromatic and luminance information for a given colour and is modelled after the OS, the L*a*b* colour space was selected as the colour space of choice used in this thesis. As a result of this, every single stimulus presented in the experiments reported in this thesis was specified in the L*a*b colour space (see Figure 4.21 for an illustration of the L*a*b colour space).

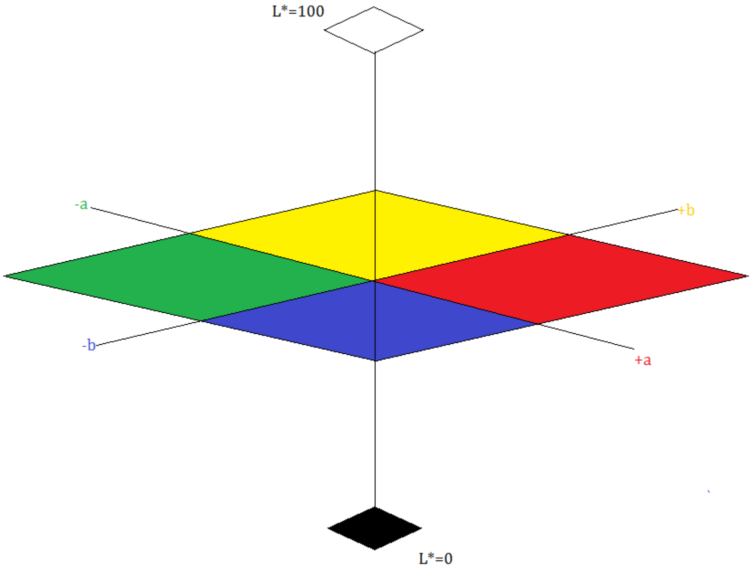

Figure 4.21: Potential colour diagnostic objects measured in Experiment 1. +L axis represents the white reference point while the –L represents the colour black. On the horizontal axes are the opponent pairs, where the +a represents the colour red and –a represents its opponent pair green. The yellow and blue opponent pair is represented by the +b and –b axes

4.5 Stimulus Generation

Because the identification of CDOs is essential to the overall aim of this thesis, the stimulus used in the main experiment must meet two very important requirements. According to Biederman and Ju (1988) and Tanaka and Presnell (1999), every CDO must be perceptually experienced in a typical hue under normal condition. The human primate must also have knowledge that the CDO is associated with a typical hue, and thus be able to reject an incorrect colour presentation if the object is presented in a non-prototypical colour in the physical world.

In light of this, seventy-two line drawings of potential CDOs were collected from the Internet and used during the first study (see Figure 4.23 for a detailed look at each of the potential CDOs measured in the first experiment). Because the aim of the main study is to explore the colour knowledge of CDOs, not their associated memory colours, objects with a low degree of naturalness were selected (see section 3.6 and section 3.7 for a reminder of the difference between colour knowledge and memory colour). All line drawings were segmented from their original background and each object was resized to an equal size and contrast, using the photo editing software GNU Image Manipulation Program (GIMP). Object's average size was subtended 13.9 deg x 14.1 deg visual angle, while the largest was subtended 16.9 deg x 14.1 deg visual angle and the smallest subtended 13.8 deg x 12.0 deg visual angle precisely. Using MatLab with the Psychophysics toolbox-3 extension (Brainard; 1997; Pelli, 1997; Kleiner et al, 2007), each line drawing was converted into a homogenous achromatic version, using the following L*a*b* values: L*= 51, a* = 0, and b*= 0.

Potential colour diagnostic objects	Colour diagnostic object Type	Potential typical hue
Banana	Natural fruit	Yellow, Green
Broccoli	Natural fruit	Green
Carrot	Natural fruit	Orange
Construction Cone	Man-made	Orange or yellow
Cherry	Natural fruit	Red
Christmas Tree	Man- made	Green
Coke Logo	Man- made	Red or white
Eggplant	Natural fruit	Purple or blue
Fire Extinguisher	Man-made	Red
Starbuck Logo	Man-made	Green
Lettuce	Natural fruit	Green
Lobster	Natural animal	Orange
McDonalds Logo	Man-made	Yellow or Red
Horse	Natural animal	Brown, or gray
#1 Pool Ball	Man-made	Yellow
British Post Box	Man-made	Red
Pumpkin	Natural fruit	Orange
Leaf	Natural fruit	Green or yellow
Stop sign	Man-made	Red or white
Strawberry	Natural fruit	Red
Tangerine	Natural fruit	Orange
Tennis Ball	Man-made	Green or white
Violin	Man-made	Brown
Twitter Logo	Man-made	Blue or white
Apple	Natural fruit	Red, green, yellow
Basketball	Man-made	Brown
Book shelf	Man-made	Brown
Butterfly (Lycaenidae)	Natural Animal	Blue, yellow, red
Candle	Man-made	Cream
Chocolate bar	Man-made	Brown
Water bottle	Man-made	Multiple
Ford Logo	Man-made	Blue and white
Hand Bag	Man-made	Multiple
Chair	Man-made	Multiple
Flower	Natural plant	Multiple
Magician Hat	Man-made	Black
Bowtie	Man-made	Black or white
Heels	Man-made	Multiple
Trench Coat	Man-made	multiple
Coffee Mug	Man-made	Multiple
Pen	Man-made	Multiple
Pencil	Man-made	Orange
Hairbrush	Man-made	Multiple
T-Shirt	Man-made	Multiple
Chuck Taylor trainers	Man-made	Black & White
Table	Man-made	Multiple
Umbrella	Man-made	Multiple
Teddy Bear	Man made	Brown
Audio Cassette	Man-made	Black
Bullet	Man-made	Silver
World globe	Man made	Blue & Green
House	Man-made	Multiple
Pair of dice	Man-made	White & Black
Donkey	Natural	Gray
Hotdog	Man-made	Brown
Apple Earphone	Man-made	White
Picasso Painting	Man-made	White & Black
Chess Piece	Man-made	White & Black
Dove	Natural Animal	White
Hammer	Man-made	Brown & Black
Tea Kettle	Man-made	Gray
Keyboard	Man-made	Black & White
Computer Mouse	Man-made	Black
Nail	Man-made	Gray
Tea cup	Man-made	Multiple
Pound coin	Man-made	Gold
Power cord	Man-made	Black & White
Hockey Puck	Man-made	Black
Rain drops	Natural	Transparent or blue
Gold watch	Man-made	Gold
Zebra	Natural animal	Black & White
Window	Man-made	Transparent

Table 6.2: Potential colour diagnostic objects measured in Experiment 1. 72 line drawings converted into homogenous achromatic versions with their associated CDO type and the hues human primate may associate with them. When the potential CDO is typically associated with multiple hues, the world multiple was used to represent the object's potential typical hues.

4.6 Squared colour patches

In the first experiment, squared colour patches were used in order to identify which of the seventy-two potential CDOs are in fact true CDOs. Using MatLab with the Psychophysics toolbox-3 extension (Brainard; 1997; Pelli, 1997; Kleiner et al, 2007), a total of eight two-dimensional squared colour patches subtended 2.29 deg x 2.9 deg visual angle were generated. The hue of each squared colour patch corresponded with one of the eight following universal basic colour categories: blue, green, yellow, purple, brown, orange, red or grey (see section 3.3.2 for more on universal basic colour categories). For the red patch, the standard R'G'B' values - R'= 255, G'= 0, B'= 0 were linearly transformed using the MatLab function "*rgb2lab*" to their equivalent L*a*b* values - L*= 53, a* = 80, and b*= 67, and later used to specify the colour of the red patch. As for the green patch, the standard R'G'B' values - R'= 0, G'= 255, B'= 0 were linearly transformed to their equivalent L* a*b* values – L*= 87, a* = -86, and b*= 83, and used to specify the colour of the green patch. For the blue patch, the standard R'G'B' values - R'= 0, G'= 0, B'= 255 were linearly transformed to their equivalent L* a*b* values - L*= 32, a* = 79, and b*= -107, and also used to specify the colour of the blue patch. With the following standard R'G'B' values - R'= 255, G'= 255, B'= 0, which also linearly transformed to their equivalent L* a*b* values, the yellow patch was specified in the following L*a*b* values - L*= 97, a* = -21, and b*= 94. The purple patch, using the standard R'G'B' values - R'= 255, G'= 0, B'= 255, was specified using the following L* a*b* values - L*= 60, a* = -98, and b*= 60.

Because the colours brown and orange have no standard R'G'B' values, the R'G'B' values perceptually known as brown and orange were consciously selected and later verified by presenting a different set of RGB values to a test subject, who did not partake in any of the experiments reported in this thesis. As a result of this, for the brown patch, the R'G'B' values - R'= 165, G'= 42, B'= 42 were linearly transformed to their equivalent L* a*b* values - L*= 37, a* = 49, and b*= 30, used to specify the colour of the brown patch, while for the orange patch, the R'G'B' values - R'= 255, G'= 165, B'= 0 were linearly transformed to their equivalent L* a*b* values - L*= 74, a* = 23, and b*= 78, used to specify its colour. Finally for the grey patch, the standard R'G'B' values for grey - R'= 128, G'= 128, B'= 128 were linearly transformed to their equivalent L* a*b* values - L*= 53, a* = 0, and b*= 0, and later used to specify the colour of the grey patch.

4.7 Experiential rating scale

An experiential rating scale was also used during the first experiment, designed to explore whether observers would report any of the true CDOs as an object which constitutes a high percentage of objects in their normal day to day visual environment. The scale was generated using MatLab with the Psychophysics toolbox-3 extension (Brainard; 1997; Pelli, 1997; Kleiner et al, 2007). The colour of the scale and the phenomenological descriptors written on the scale were specified in the following L*a*b* values: L*= 51, a* = 0, and b*, while Times New Roman lower case font type which average size subtended 2.2 deg x .60 deg visual angle for the phenomenological descriptors. The scale had the total of six phenomenological descriptors - never, rarely, somewhat, occasionally, frequently and always - which represented the strength of an observer's visual experience in relation to the presented CDO and more importantly corresponded to whether each of the presented CDO constitute a highs percentage of the objects in the observer's visual environment. Each phenomenological descriptor was presented 4 inches apart from the scale and had a numerical value with 0 being the lowest experimental value and 5 being the strongest experimental value.

4.8 Generating control stimulus

For the first experiment, the control stimulus was generated using the same exact produces used to generate the squared colour patches described in section 4.6. However for the control stimulus, each patch was exactly subtended 13.9 deg x 14.1 deg visual angle. This size was selected to match the average size of the seventy-two potential CDOs described in section 4.6. There was a total of 8 control stimuli which were designed to match, in colour, the squared colour patches.

4.9 Generating typical, and atypical hues, and their colour categories

With respect to the main study, which is discussed extensively in chapter 5, an object Stroop-task was employed. Because of this, it was important that the typical and atypical hues associated with the true CDOs potentially observed in the first experiment are systematically generated when they are presented in the main study. Using MatLab with the Psychophysics toolbox-3 extension * Brainard; 1997; Pelli, 1997; Kleiner et al, 2007), each of the typical and atypical hues used in the main study were specified in the exact same L*a*b* values as the squared colour patches detailed in section 4.6. In a case of a true CDO, whose known actual colour strongly corresponds to, for example, a red hue, when the hue is presented to a given observer in the main study, this hue was presented in the following L*a*b* value - L*= 60, a* = -98, and b*= 60 (see section 4.6 for specific L*a*b* values associated with each of the typical and atypical hues presented in the main study). As for the actual colour category associated with the true CDOs potentially observed in the first experiment, each colour category was written in Times New Roman small case font, in a size 36.

4.10 Observers

After receiving an ethical approval for the first and main study through the University of St Andrews Ethical committee (ethical approval number: PS10991, see ethic form for more), St Andrews university students, both undergraduates and postgraduates, were recruited using the University of St Andrews SONA system. Through this system, observers were pre-screened for normal colour vision. Twenty-four observers were eventually recruited to take part in both experiments. In the beginning of each experiment – in both the first and the second study - observers were screened for normal colour vison using the Ishihara colour plates, presented to each observers on a Dell 2407WFP monitor powered by NVIDIA GeForce GTX 650 graphics card with a spatial resolution of 1152 x 864 pixels and a refresh rate of 60 Hz (see section 4.3.1 for apparatus specifics). Observers were asked to read and sign the following documents - participation information sheet, participation consent form and the participation debrief form. After the completion of both experiments, observers were compensated a total of 10 pounds each.

4.11 The presentation of the first experiment

With the techniques and methods used to design the first and second experiment already addressed, I will now explain the overall aim of the first experiment, which is broken into two parts, in great detail. This will be followed by the results of the experiment, of both part 1 and part 2, while the implication of these results as it relates to the main experiment will be discussed in chapter 5.

4.12 Experiment 1: Identifying high colour diagnostic stimulus

The overall aim of part 1 is to identify, using a colour decision-time task, stimuli observers define as true CDOs. As previously noted, for a given object to be considered a CDO, it must meet two requirements. The first requirement pertains to the idea that the object must be perceptually experienced in a typical hue. If a stimulus is in fact experienced in a typical hue, during each stimulus presentation, observers on average should select a single squared colour chip which corresponds to this hue. In part 1 of Experiment 1, this requirement was measured by taking the squared colour patch responses of each stimulus per observer and obtaining a typicality average for each stimulus. As a result, a stimulus for which observers typically selected a single squared colour chip (higher typicality average) was known to have met the first of the two requirements.

The second requirement pertains to the idea that observers must know that the object is strongly associated with a typical hue, information which is typically included in the object's representation as the object's prototypical colour (or the prototypical representation of the object's typical hue). When observers are presented with a stimulus whose typical hue is commonly known they should be easily able to discount all of the stimulus' atypical squared colour chip presentations – non-prototypical colours - and should on average select the typical hue known to be associated with the presented stimulus faster than when presented with a stimulus whose typical hue is not commonly known or agreed upon. In this experiment, such requirement was measured by obtaining the average decision-time score for each stimulus per observer across the twenty-four observers. Thus, a stimulus with a low average decision-time score was known to have met this second requirement. As it relates to the identification of a true CDO, a given stimulus must firstly yield a high typicality average and secondly must also yield a low average decision-time score in order to be considered a true CDO.

4.12.1 Observers

With the aim to identify true colour diagnostic stimuli in mind, twenty-four observers from the University of St Andrews with normal colour vison participated in this study. Each observer was screened for normal colour vison using the Ishihara colour plates (Ishihara, 2004), presented on a computer monitor. The experiment took approximately thirty-five minutes. After the completion of the first part of the experiment, observers took a five minute break as they waited to begin part 2.

4.12.2 Apparatus

A Dell 2407WFP gamma corrected monitor powered by NVIDIA GeForce GTX 650 graphics card with a spatial resolution of 1152 x 864 pixels and a refresh rate of 60 Hz was used. The background of this monitor was black and set to a constant luminance value of 23 cd/m^2, which was half of the monitor's maximum luminance value of 46 cd/m^2. Approximately 51 cm away from the computer monitor was a chin rest in which observers were required to place their chin throughout the entire experiment. The computer mouse was used to record squared colour patch responses and how long it took observers to make their responses. Observers' responses and decision-time scores were stored and immediately written to a separate text file. The entire experiment was written in MatLab with the Psychophysics toolbox-3 extension (Brainard; 1997; Pelli, 1997; Kleiner et al, 2007).

4.12.3 Decision-time scores: alternative methods

It is worth noting that a mouse input is not the only way decision-time scores which are reported in this thesis could have been measured. In fact there are at least three different ways decision-time (or reaction-time) scores are typically measured in colour perception and other related fields. For example in some studies keyboard inputs are used to measure decision-time scores. However the risk in using such method is that observes in some conditions may have to search for a given keyboard symbol as they attempt to confirm their decisions. Given that most experiments are conducted in the dark along with the slight head movements observers will most likely make as they attempt to recover a given symbol, this recovery methods can significantly influence the average decision-time scores obtained during a given experiment. Another option is to record decision-time scores by instructing observers to give verbal responses. This method is also problematic as observers generally think about what they are going to say before they actually verbalize their responses. Also when we consider individual differences among observers, there are some observers who verbalize quicker than others. With this in mind, a verbal response may also be equally as problematic as keyboard inputs. Finally another method of input, which is the most common method used, is the use of a push pad. On one level, this removes any search or verbal interference during observers' responses. However on another level, when we consider the handedness of observers there could potentially be a confound in the average decision-time scores obtained. For example with at least two colour choices as it is the case in all of the experiments reported in this thesis, , right handed observers may be faster at selecting colours located on the right hand side while the recovery of colours located on the left side may be much slower; the inverse may also be true for left handed observers. Nonetheless the mouse input was selected for all of the experiments reported in this thesis because: (i.) observers do not have to verbalize their responses nor search for a given keyboard symbol and (ii.) by using the mouse input handedness is controlled for as observers are able to use their dominant hand to control the mouse as they attempt to give a particular input.

4.12.3 Stimuli presentation

At the beginning of each trial a grey fixation point on a black background was presented for 1000ms in which observers were instructed to fixate[13]. Immediately after, an image (i.e. a potential colour diagnostic object) was presented until a colour response was given. Seventy-two outlined drawings converted into

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[13] Due to pragmatic and technical limitations, eye movements was not measured which may not have informed the overall result or changed dramatically the results which was eventually obtained in this experiment. Furthermore with respect to the colour diagnostic object literature it is a constant practice that when identifying the prototypical colour associated with a given colour diagnostic object the monitoring of eye simply does not give us additional information.

achromatic versions were individually presented exactly in the middle of the computer monitor along with twenty-four 13.9 deg x 14.1 deg visual angle homogenously squared colour patches, serving as the control stimuli. Towards the bottom of the computer monitor, eight squared colour patches were presented horizontally, with two inches between each one[14]. Each squared colour patch represented one of the universal basic colour categories. In order to avoid any negative decision-time effect, opponent squared colour patches (e.g. red patch and green patch) were never presented next to each other. Because the squared colour patches were presented horizontally from left to right and thus, in some conditions, it may have taken observers to select the squared colour patches on the extreme ends of the squared colour patch spectrum, an equal amount of the homogenously squared colour patches - three in total, were presented in order to counterbalance for any false decision-time effects (see Figure 4.23 and Figure 4.24 for examples of stimuli presentation). All of the stimuli presented were completely randomized.

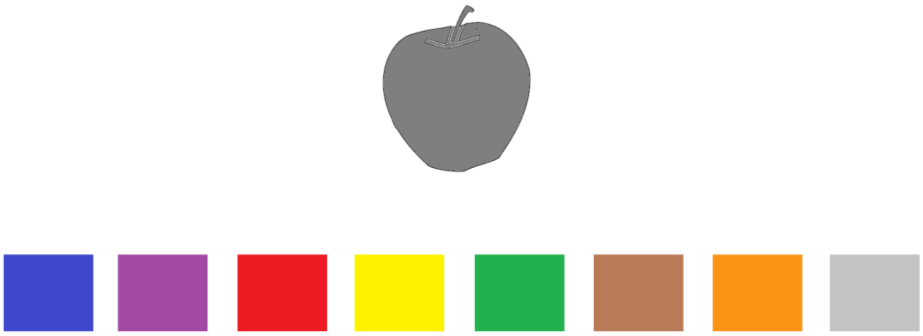


Figure 4.23: Stimuli presentation of a potential colour diagnostic object. This figure illustrates a presentation of a potential CDO in the form of an apple. Towards the bottom of observers' visual field is the presentation of eight squared colour patches.

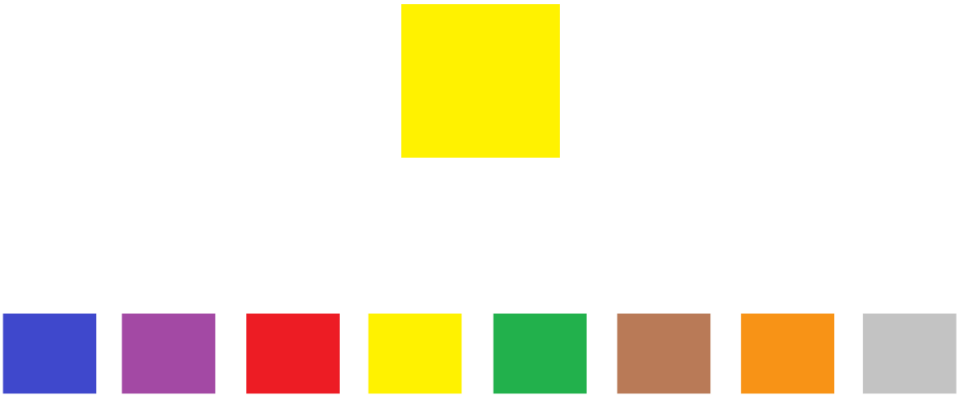


Figure 4.24: Stimuli presentation of a homogenously squared colour patch. In this presentation, a yellow homogenously squared colour patch is presented as the control stimuli. All observers have to do in this trial is to match the homogenously squared colour patch to its matching squared colour patch.

4.12.4 Procedure

Observers' task was exactly the same as the task observers performed in the Witzel, Valkova, Hansen and Gegenfurtner (2011) study. In a completely dark room, observers began by placing their chin on a chin rest which held observers' heads in a fixated position. Observers were then instructed to read twice out loud the instructions for the experiment, presented in the middle of the computer monitor. Following this, observers were asked to explain the instructions back to the experimenter while keeping both eyes on the screen. This not only guaranteed that observers understood the task they were to perform but also made certain that observers had adapted to the neutral background of the computer monitor. Each trial began with the disappearance of the mouse cursor followed by a 500ms presentation of a small grey circled fixation point in the middle of the screen. Immediately after, each stimulus was presented in the middle of the screen for 1000ms, along with a presentation of eight squared colour patches located at the bottom of the screen.

Observers' task was to first judge the presented stimulus. Once observers were ready to move the mouse, the mouse cursor would appear always at the centre of the screen. As fast and as accurately as possible, observers had to select one of the squared colour patches they judged to be the known typical colour associated with the stimulus, using the left click on the mouse. Once a single squared colour patch was selected, the mouse cursor disappeared, mask presentation lasting 100ms appeared and a new trial began. There were a total of ninety-six trials. No stimulus except for the homogenously squared colour patch was presented more than once as this would create a stimulus-specific automatisation of observers' responses. The selection and the decision-time associated with each squared colour patch per stimulus was stored and later computed using IBM Statistical Package for the Social Sciences (SPSS) Statistics 22 (IBM Corp, 2013).

4.12.5 Experiment 1: Stimuli with an average typicality higher than 95%

For each stimulus, the squared colour patch selected as well as the time it took an observer to select it was recorded. There were a total of twenty-four recorded squared colour patches selected for each stimulus and ninety-six decision-time scores recorded in total per observer. For each stimulus, the squared colour patch frequently selected across all twenty-four observers as the hue they judged as the object's known typical hue was obtained. The most frequently associated squared colour patch was later known as the stimulus' typical hue, however, this did not automatically mean that object met the first requirement of a given CDO. Similar to the Witzel, Valkova, Hansen, and Gegenfurtner (2011) study, 95 % of all observers must agree on typicality. In this study, that meant that twenty-three out of the twenty-four observers had to agree that the stimulus, when presented in the physical world, typically appears in a single hue, corresponding to the hue of one of the squared colour patches. As a result of this, stimulus with an average typicality lower than 95% was discarded.

In Figure 4.25 and Figure 4.26, the result for each stimulus is plotted with its associated Standard Error (SE). The yellow line across the graph represents the average typicality score for the control stimuli across all observers, which yielded an average typicality score of 95.6%.

Due to the 95% cut off mark, only nine stimuli had an accuracy typicality score ≥ a 95% accuracy rate. The first stimulus observed was a banana, which observers typically associated with a yellowish hue, with an average accuracy rate of 95.8 % and a SE of .042. The next stimulus was a broccoli, which observers typically associated with a greenish hue, with an average accuracy rate of 95.8 % and a SE of .042. Following this stimulus was a cherry, which was typically associated with a reddish hue, also with an accuracy rate of 95.8% and a SE of .042. The fourth stimulus was a Christmas tree, typically associated with a greenish hue, with an average accuracy rate of 95.8% and a SE of .167. As for the fifth stimulus, this was the Coke logo, typically associated with a reddish hue, with an accuracy rate of 95.8% and a SE of .042. The sixth stimulus was a fire extinguisher, typically associated with a reddish hue, with again an accuracy rate of 95.8% and a SE of .042. The seventh object was a leaf, typically associated with a greenish hue, with an accuracy rate of 95.8% and a SE of .042. The eighth stimulus was a strawberry, associated with a reddish hue, with an accuracy rate of 95.8% and a SE of .167. The last stimulus – table - comes as a surprise since it is quite clear that tables appear in various hues in the physical world. However, for this group of observers, the table was associated with a brownish hue with again an accuracy rate of 95.8% and a SE of a .167. For other stimuli such as rain drop, stop sign, apple, or Starbucks logo, accuracy rate came very close to 95% because less than twenty observers agreed on the typicality of these objects (see Figure 4.25 and 4.26 for the complete results for all the potential CDOs tested in this experiment).

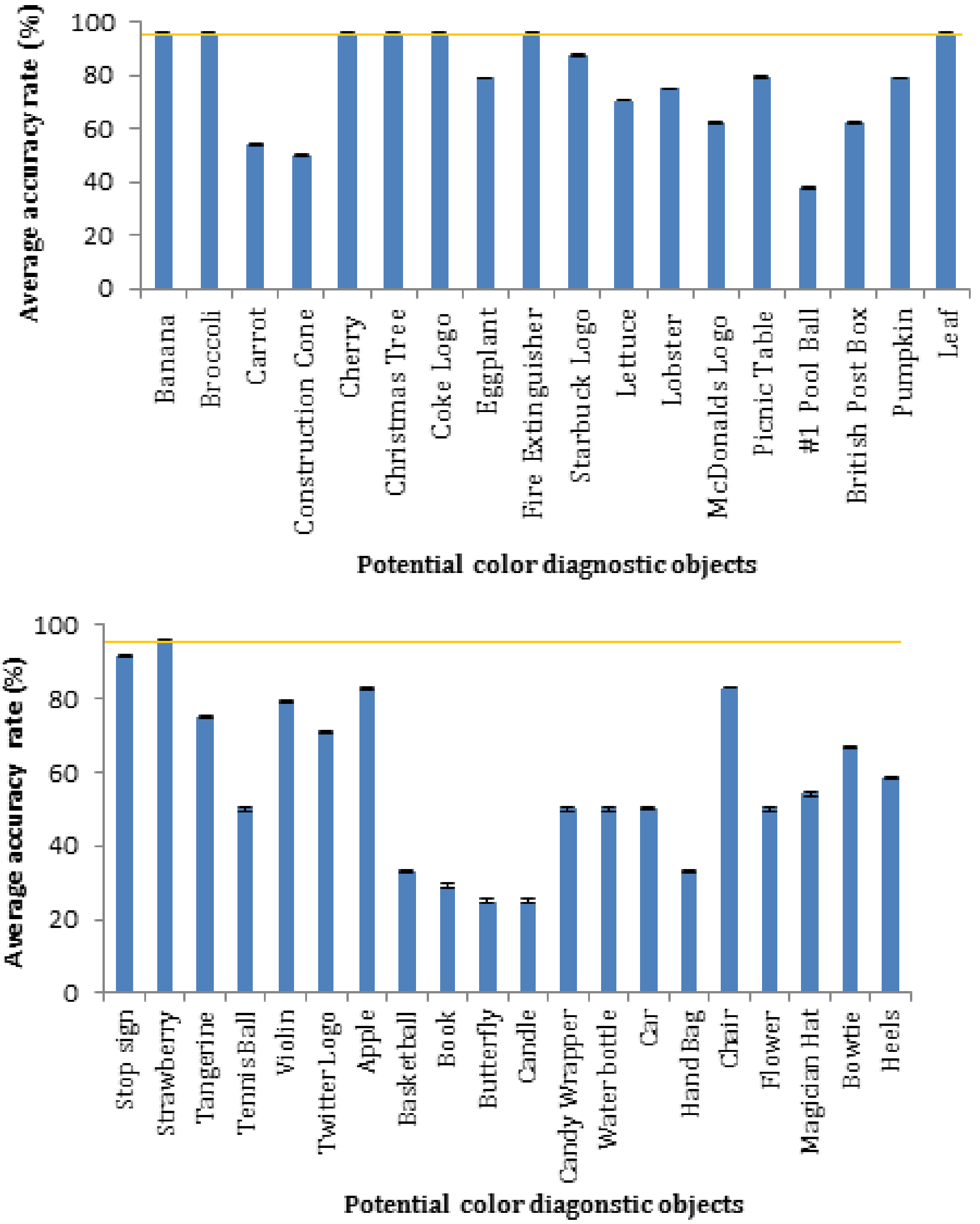
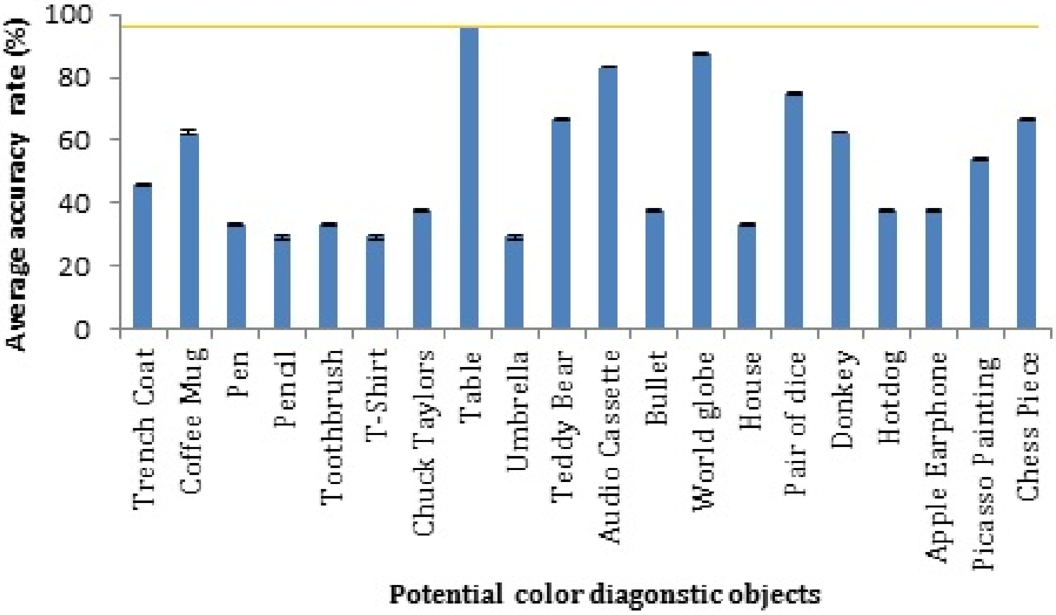


Figure 4.25: Results for potential colour diagnostic objects. On the y axis is the average typicality score (or accuracy rate) across all twenty-four observers in percentage and their associated SE. In simple terms, this represents how often observers agreed on the typicality for a given stimulus. On the x axis each of the potential colour diagnostic objects is represented. The yellow line represents the average accuracy rate for all of the control stimuli across all twenty-four observers which yielded an accuracy rate of 95.6%.



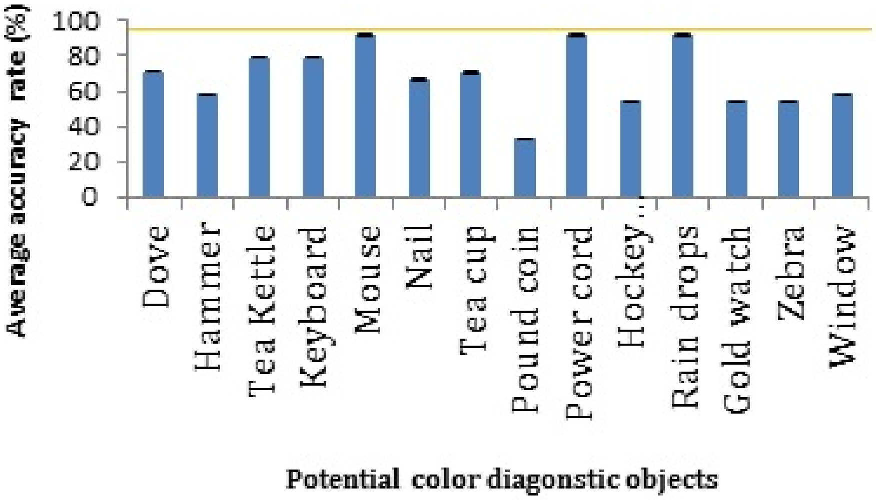


Figure 4.26: Results for the second wave of potential colour diagnostic objects tested. Several points are worth noting as it relates to this graph. The first is that the table is the only potential colour diagnostic object that yielded a high enough average typicality score. This may come as a surprise as tables typically appear in the physical world in multiple hues. Secondly, because white and black squared colour patches were not included in this experiment, objects which typically appear in these two colours were often synthesized by the observers. As a result of this, observers often selected the grey squared colour patch, which led to an average typicality score close to the 95% cut off mark. As for the objects which appear in multiple hues when presented in the physical world, with the exception of the table, they often yielded a low typicality average which was among the lowest when compared to the other potential colour diagnostic objects tested in this experiment.

4.12.6 Experiment 1: Stimuli which yielded low average reaction score

Although stimuli which yielded a 95% average typicality score or higher were given special attention, an average decision-time score was obtained for all of the stimuli tested in this experiment, by collapsing each of their decision-time scores across all twenty-four observers. Each stimulus' decision-time score was later compared to the average decision-time score associated with the homogeneously squared colour patches

– the control stimuli, as these stimuli's average decision-time score served as the baseline decision-time score. The reason for this decision is simple. Because for these stimuli, all observers had to do was match each homogeneously squared colour patch to its corresponding squared colour patch specified in the same exact hue with the only difference being their size (e.g. yellow homogeneously squared colour patch matched to its corresponding yellow squared patch), observers response times should be the lowest when compared to the potential CDOs included in the experimental conditions. In other words, observers' hue responses for the homogeneously squared colour patches did not require any form of retrieval, just pure colour matching. Thus, for a given stimulus' average decision-time score to be considered a low enough average decision-time score, it must either be in the same region or lower than the average decision-time score of the control stimuli. In Figure 4.27 and Figure 4.28, the average decision-time scores across all observers for each stimulus are plotted with their associated SE.

Because a given CDO must not only have a high typicality average but also a low decision-time score, the stimuli previously noted as having a typicality average equal to or above 95% typicality average were given special attention. In Figure 4.27 and Figure 4.28, the yellow line across the graph represents the average decision-time score for the control stimuli, averaged across all twenty-four observers, which in this case was 1.85secs with SE of .088. When comparing the nine stimuli which yielded a typicality average equal to or above 95%, it becomes undoubtedly clear that these stimuli also seem to have a low average decision-time score, below or very close to the average decision-time score observed for the control stimuli. For example for the first stimulus – banana, a very low average decision-time score of 1.63secs with a SE of .108 was observed. As for the broccoli, an average decision-time score of 1.93secs with a SE of .441, which is very close to the average decision-time score of the control stimuli, was observed. Following this was the cherry, which yield an extremely low average decision-time score of 1.51secs with a SE of .141. Next was the fourth stimulus - Christmas tree, which also yielded a very low average decision-time score of 1.54secs with a SE of .122. The fifth stimulus was the Coke logo which yielded a decision-time average of 2.31secs and a SE of .690. The sixth stimulus – leaf, yielded a decision-time score of 2.32secs with a SE of .666. The seventh stimulus which yielded the highest average decision-time score of 2.44secs with a SE of .988 was a fire extinguisher. Following this was a strawberry, which yielded average decision-time of 2.03secs with a SE of .395, while the last stimulus was a table, which yielded an average decision-time of 1.91secs with a SE of .454. It seemed that for these stimuli, observers were able to quickly discount the non-prototypical colours (i.e. atypical hues) presentation and with the automatic activation of these stimuli's prototypical colour, primarily included in the representation of these objects, observers were able to recover their known typical hue. Due to these objects' high typicality score (1st requirement for CDOs) and low decision-time scores (2nd requirement for CDOs), when compared to the other potential CDOs measured, these were identified as the true CDOs.

It is further worth noting that many of the average decision-time scores for the other potential CDOs measured in this experiment were significantly above the average decision-time of the control stimuli (e.g. lettuce, #1 pool ball, basketball, Twitter logo, Starbucks logo, rain drop). The potential CDOs which had an average decision-time score close to the average decision-time of the control stimuli (e.g. stop sign, lobster, eggplant, McDonald's logo, tangerine, chair, Twitter logo) had an average typicality score close to the 95% cut off mark. In other words, the average typicality score and decision-time seems to co-vary. Thus, the higher the typicality score, the lower the average decision-time score observed for the given stimulus.

4.12.6.1 Evaluating the current paradigm

4.12.6.2 Emphasis on high colour diagnostic objects

After the initial omission of four-eight potential CDOs (e.g. tree branches, raspberry, American flag, sport car, red brick, Caucasian skin, beach sand, and so forth) , and having started experiment 1 with approximately seventy-two potential CDOs, the aim of experiment 1 was to obtain CDOs with high colour diagnosticity (Please see section3.1 for more on the distinction between HDOs and LDOs) . Because of this, it is very possible that legitimate CDOs were omitted. However it is important to keep in mind that most of the CDOs eventually omitted were mostly LDOs. Moreover if the selection of LDOs was allowed this will introduce colour effects which could not have been directly controlled for as LDO generally have more than one or two legitimate CNPs whereas HDO only have one and in rare cases two legitimate CNPs. Therefore it would be more difficult to attribute any effect obtained in the main experiment to a single colour as it could equally be all of the colours LDOs are naturally presented in. For example stimuli such #1 pool ball, Twitter logo, and the Starbucks logo were eliminated because when you closely examine the experiential nature of these objects, they are typically presented in a wide range of colours although they also have a prototypical colour. For example the Twitter logo although is associated with a blue hue, it is also presented in pink, green, brown, orange and so many other colours. On the other hand, a leave or a banana only has one or two legitimate CNPs, colours which we are directly able to measure its effect in the main experiment.

4.12.6.2.1 Cut-off consideration

With respected to recording decision-time as it is commonly done to measure the colour diagnosticity associated with a given object, there is an inherent arbitrary nature which accompanies the selection processes of a given stimuli used in the studies reported in all this study, namely those reviewed in chapter 3 as well in the main experiments reported in this thesis. For example when we consider all of the studies reported in chapter 3, none of these studies, but one, measured colour diagnosticity associated with a given stimuli. In other words colour diagnosticity was assumed. In the study which colour diagnosticity was measured - Witzel, Valkova, Hansen and Gegenfurtner (2011), researchers in this study prioritized certain group of stimuli (e.g. those which covered a different point on the colour space) during the selection process independent of the high decision-time scores these objects demonstrated. For example during the Identification of high colour diagnostic stimuli, a cut off value was set to average decision-time score obtained for the control stimuli as this value is not influenced by any top down effects. Thus the stimuli closest to this value was selected as the stimuli of choice. The question now arises what about the Coke logo, and the fire extinguisher which have higher apparent reaction times, and larger standard errors selected among the stimuli selected in the main experiment? In this studies the focus was not only selected object with high colour diagnosticity but those considered modern colour diagnostic object – object which are commercially based products such as Coca-Cola or objects or CDOs with a single but complex colour distribution such as the fire extinguisher, as these objects generally have a high exposure value and still meet to high degree the colour diagnostic requirements (Ly and Hardeberg, 2013).

4.12.6.3 Colour patch arrangement

Considering the overall decision-time scores obtained in experiment 1, a possible negative effect on decision-time scores could have occurred due to the way squared patches were arranged as illustrated in Figure 4.23. For example if a potential CDO was presented and the colour a given observer decides to select is located at the far end of the colour spectrum – blue and grey[15], this may have influenced the overall decision-time scores for these CDOs when compared to the CDOs associated with a squared patch located in the centre of the colour spectrum - those easier to select. As a result of this, squared patches could have been presented in a circle around the potential CDO's centre ultimately controlling for the distance between the squared patched and the object. While this could have been the case, decision-time scores for control objects, namely blue, grey coloured chips, demonstrated, among the controlled objects, the lowest average decision-time scores when compared to other controlled objects. This suggests that observers knowing after several trials, that certain squared patches were located on the extreme end of the colour spectrum, focused harder on selecting the squared patches in conditions when theses patch needed to be selected. This in turn yielded a much faster decision-time score. It may have also been that the distance between the squared patches and the potential CDOS were not significant enough to significantly influence the overall decision-time scores observed, a position this thesis supports.

4.12.6.4 Non-colour related properties

Another issue which may have influenced decision-time scores are the role of non-colour related properties – identifiability and accessibility. With respect to identifiability, this means that for some CDOs, because of their low naturalness, observers may have had a difficult time identifying the object in question which would have then influenced how quickly its prototypical colour is recovered. To control for this, as mentioned in section 4.12.6.2, forty-eight potential CDOs were initially removed due to the fact that observers may have had a hard time identifying these objects. Furthermore it is still possible that for the seventy- two potential CDOs tested observers still had a hard time identifying these objects. However this inability to quickly identify these types of objects may have been due to the fact these object are inherently subordinate objects and thus are often confused with their superordinate counterparts as actually due to the presentation of the object *per se*.

This leads us to the question of accessibility. For example some potential CDOs may have been easier to access and thus recover because they represent the superordinate or prototypical object within that particular category (i.e. banana vs avocado). The question now becomes is it possible to separate accessibility from colour prototypicality. In other words, an object that is more accessibility may be due to

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[15] Please note there was only 6 objects which a high number of observers - < 95%, selected blue or grey as the objects actual prototypical colour.

the fact the object has a prototypical colour, however it could also be more accessible due to other non-colour related properties – shape, size, as these may be the feature which allows the object to enjoy quicker accessibility. As a result accessibility could have been better controlled as object with the same level of accessibility would have yielded a strongest decision time scores, however this will have significantly reduced the number of potential CDOs measured in experiment 1.

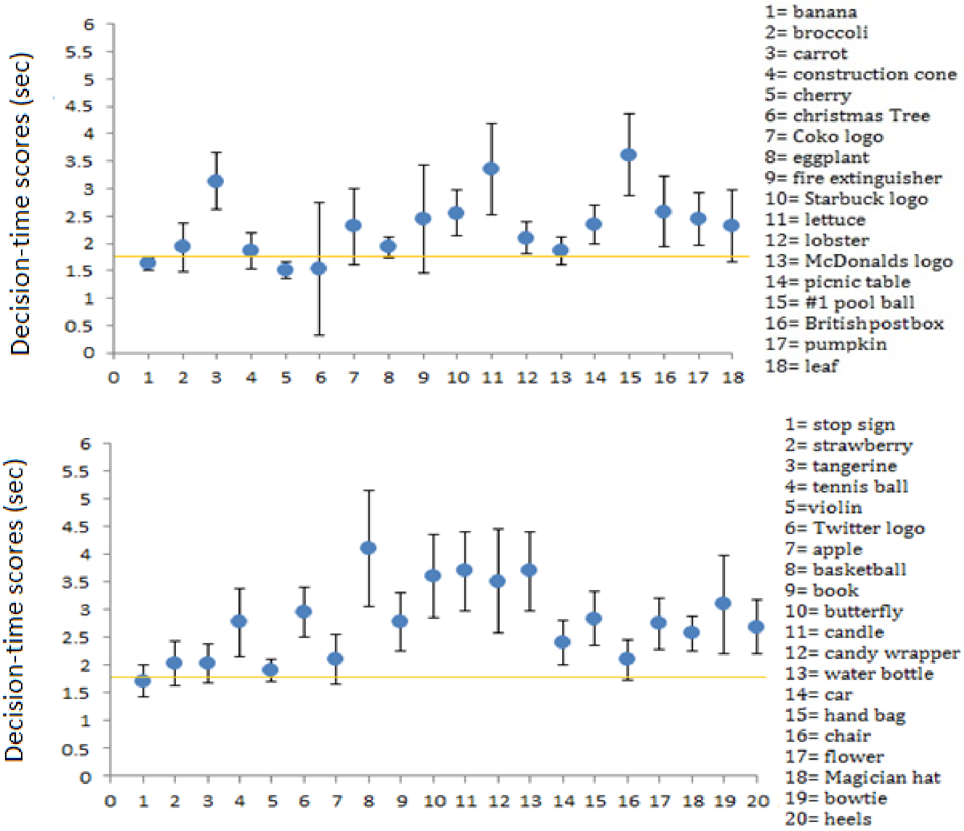


Figure 4.27: Decision-time results for the potential colour diagnostic objects tested. The first thirty-eight potential colour diagnostic objects and their average decision-time scores across all observers are plotted. On the y axis is the average decision-time score in seconds and the associated SE is represented. The x axis, using the key in the top right corner, represents each potential colour diagnostic objects. The yellow line represents the average decision-time score for the control stimuli.

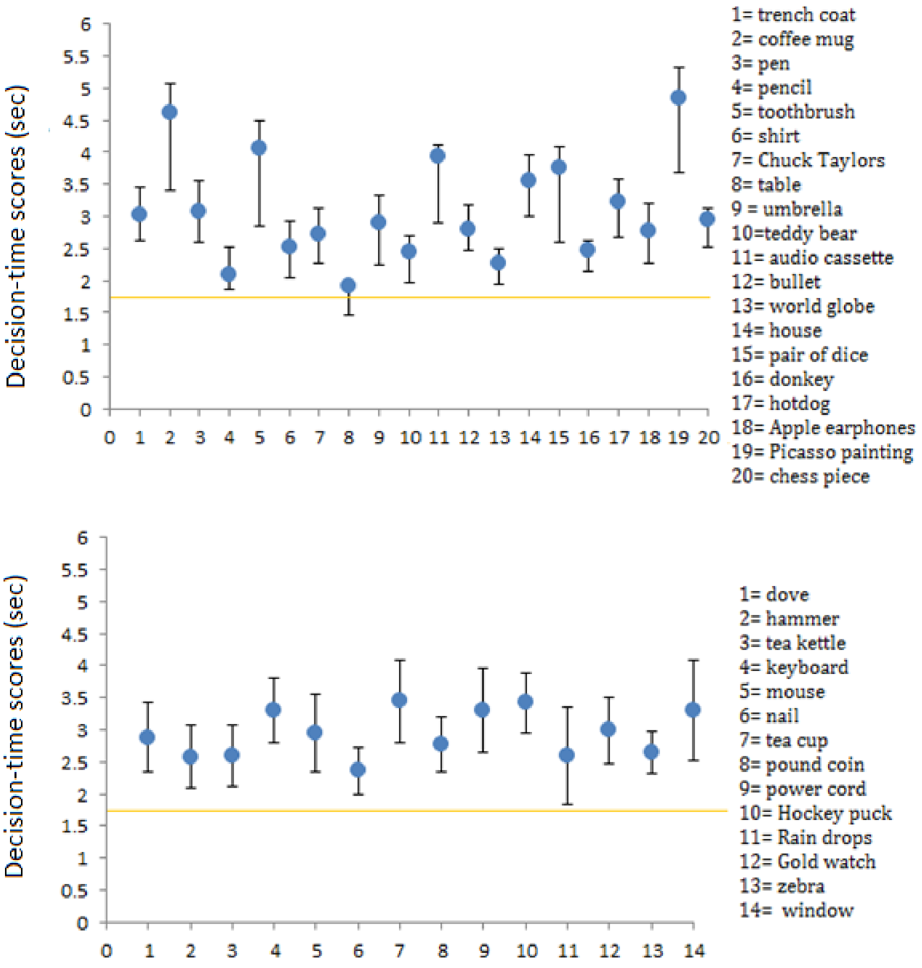


Figure 4.28: Second wave of results for the decision-time s of the potential colour diagnostic objects tested. Notice that the table, as in the typicality results for this group of potential colour diagnostic objects, is the only stimulus close to the average decision-time score observed for the control stimulus. Further notice that the objects (e.g. keyboard, zebra and computer mouse), whose typical colours observers often synthesized, typically yielded similar average decision-time score.

4.12.7 Experiment 1: Identifying frequently experienced colour diagnostic objects

In order to explore whether any of the CDOs identified in the first part of the experiment are objects which constitute a high percentage of objects surrounding individual observer's day to day visual environment, an experimental rating scale modelled after the Likert scale was employed. The aim of the experimental rating scale was to measure each observer's phenomenological experience of each CDO. With a total of six phenomenological descriptors – never, rarely, sometimes, occasionally, frequently and always - represented on the experiential scale, observers were able to select a descriptor which best describes how often the presented CDO occupies the observers' visual environment on a day to day basis. Each descriptor was given a numerical value, while the lowest descriptor – never, had an experiential value of 0 and the highest descriptor – always, was given an experiential value of 5. For any observer who phenomenologically reported their experience with a given CDO as frequently or always, this was a strong indication that this object may in fact constitute a high percentage of objects surrounding that observer's day to day visual environment. In other words, objects with an experiential value ≥4 were known as FECDOs as these objects were phenomenologically described by an observer as objects he or she frequently or always experiences on a day to day basis. On the other hand, CDOs with an experiential value < 4 were identified as ICDOs as these objects seem to be among the objects which constitute only a small percentage of objects surrounding the observer's day to day visual environment.

4.12.8 Observers

The same exact observers who participated in the first part of the experiment participated in this part. After the completion of the experiment, each observer was debriefed and received £5 for his or her participation in both parts of the experiment. This part of the experiment took approximately 15 minutes.

4.12.9 Apparatus

The same exact computer monitor used in the first part of the Experiment 1 was used in this experiment, with the same exact graphics card, spatial resolution, luminance value and distance away from the chin rest. The mouse input was used to record observer's phenomenological selections, which were stored and immediately written to a separate text file. The entire experiment was also written in MatLab with the Psychophysics toolbox-3 extension (Brainard; 1997; Pelli, 1997; Kleiner et al, 2007).

4.12.10 Stimuli presentation

Although the data for only nine outlined drawings converted into achromatic versions is reported in this thesis, the phenomenological selections of seventy-two outlined drawings converted into achromatic versions were obtained. As it relates to the stimuli presentation, seventy-two outlined drawings were individually presented exactly in the middle of the computer monitor. The order of presentation of the stimuli completely randomised using the *randperm* function in matlab pyschtoolbox. Towards the bottom of the computer monitor, an experiential scale was presented horizontally, with each phenomenological descriptor represented on the ticks of the scale. The descriptors were presented in the same font type, size and colour in order not to draw attention to a given descriptor and bias observers' response. Note that the 24 homogenously squared colour patches which served as the control stimuli in the first part of the experiment were not presented to observers in this part of the study.

4.12.11 Procedure

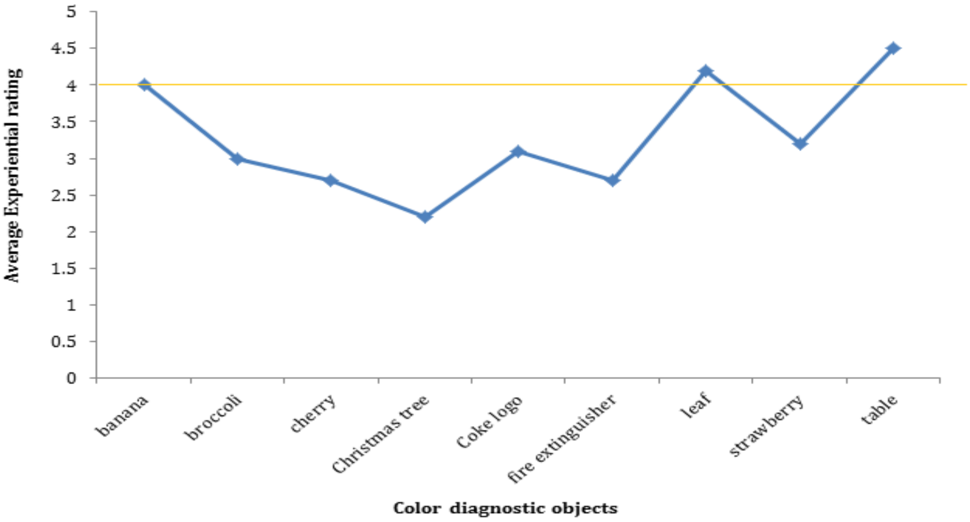
While sitting in a completely dark room, observers were asked to place their head on the chin rest. Observers were then asked to read out loud the instructions for the experiment, presented in the middle of the computer monitor. After reading the instructions, observers were instructed to explain the instructions back to the experimenter while keeping both eyes on the screen. When the observers did not clearly understand the instructions, they were asked to read the instructions again until the instructions became clear.

Each trial began with a squared fixation point in the middle of the screen, lasting 500ms. Next, each stimulus was presented in the middle of the screen. During the presentation of each stimulus, observers' task was to judge the stimulus and indicate how often they visually experience the presented stimulus on a day to day basis, using the mouse input. Unlike in the first part of the experiment, observers were given an unlimited amount of time to select a phenomenological descriptor. After the selection of a single phenomenological descriptor, the next stimulus was presented until there were no more stimuli left to present. There were a total of seventy-two stimuli presented and no stimulus was presented more than once. The phenomenological descriptor selected for each stimulus was later converted to its corresponding numeral value and the experiential value obtained for each CDO was matched to each observer.

4.12.12 Results: Average experiential value for each colour diagnostic object

Because the study was designed to explore individual observer's phenomenological experience with each of the CDO previously identified in part one of the experiment, it would be insufficient to obtain an average experiential value across all twenty-four observers. By doing this, object to which a given observer may have assigned a low experiential value – 1, 2 and 3, would be incorrectly assigned as a FECDO for those observers who assigned to the same object a high experiential value – 4, 5.

On the other hand, an average experiential value across all twenty-four observers could provide insight into the CDOs which would most likely be considered as FECDOs for most observers. In Figure 4.29, an average experiential value across all twenty-four observers is plotted. The yellow line across the graph represents the phenomenological descriptor frequently. In theory, CDOs with an average experimental value of 4 or higher should most likely be identified as FECDOs for each observer, while CDOs with an average experimental value <4 should most likely be identified as ICDOs. The Christmas tree, for example, had an average experiential value of 2.25. Thus, for most observers, this object should be assigned a low experiential value and thus be phenomenologically understood as a ICDO. On the other hand, the table yielded an experiential value of 4.58. For most observers, this object should be assigned a high experiential value and thus be phenomenologically understood as a FECDO (see Figure 4.29 for the complete results for the experiential value of the CDOs previously identified in part one of the experiment).

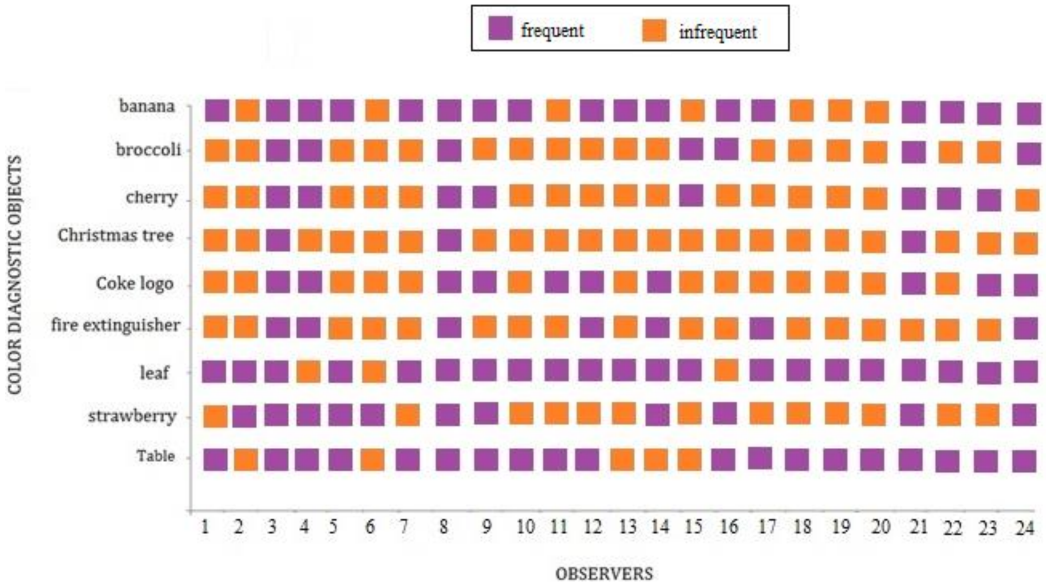


4.29: An average experiential value for each colour diagnostic object averaged across twenty-four observers. The yellow line across the graph represents the experiential value of 4. The objects (banana, table, leaf) close to this value are most likely to be phenomenologically reported by most observers as frequently experienced colour diagnostic objects. This suggests that, for these observers, these object may constitutes a high percentage of objects surrounding the observers' day to day visual environment.

4.12.13 Results: Individual observers' experiential value for each colour diagnostic object

The individual observer's experiential value for each CDO is described in Figure 24.9, where the experiential value for each CDO per observer is allocated a phenomenological category– frequent and familiar. In this figure, what is immediately noticeable is that the banana, leaf and table were, for most observers, reported as CDOs frequently experienced - FECDOs. These objects were also noted above as often having an average experiential value of 4 or higher than 4. Another phenomenological pattern worth noting is that the Christmas tree was, for most observers, reported as an object which was not frequently experienced, as most observers typically assigned this object an experiential value below 4. This is particular intuitive and easy to understand as Christmas tree is an object which only appears in a given season and thus only constitutes a small percentage of objects surrounding most human primates' day to day visual environment.

In all, objects which fell in the frequent phenomenological category were identified as FECDOs. In the most extreme case, observer 8[16] reported every single CDO as an object which he or she frequently experiences on a day to day basis (or which constitutes a high percentage of the objects in his or her visual environment on a day to day basis). On the other end, observer 2 only reported the leaf and strawberry as CDOs which constitute a high percentage of the objects in his or visual environment on a day to day basis. The objects which fell in the familiar phenomenological category were identified as ICDOs. Using observer 8 as an example again, this observer did not report any of the presented CDO as a ICDO, while in the case of observer 2, seven of the nine CDOs were reported as ICDOs (see Figure 4.30 for each observer's phenomenological experience matched to each of the CDO presented).



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[16] The result for this given observer may be due to the fact that this observer did not truly reflect upon his or her day to day experience with the CDO. It could also be that the observer did not understand the task completely. This example highlights one of reasons why phenomenological data must not be completely dependent upon but further verified. However, the greater the variability in a given observer's responses the more reliable the phenomenological data for that observer is. This was the case for most of the observers in this part of the experiment.

Figure 4.30: First person account of observers' experience of colour diagnostic objects for twenty four observers. This figure illustrates the phenomenological category – frequent or infrequent - each observer's experiential value fell into for each colour diagnostic object. For most observers, the cherry and Christmas tree typically fell in the infrequent category, while the banana, table and leaf often fell in the frequent category.

4.12.13.1 Categorisation 'frequently experienced' (FECDOs) or 'infrequent' (ICDOs)

Despite the bizarre and unsubstantiated tendency within the discourse of psychology to call into question the rigor and explanatory power of phenomenological data, it is very possible that results from first person account can tremendously inform behavioural data such as those which have been in experiment 1 but also throughout the course of this thesis. With respect to the phenomenological data presented above, one could dismiss this data by arguing that the measure of experiential value was significantly effected by accessibility. In other words when observers are instructed to give their subjective account of whether a given object is frequently experienced, the accessibility of an object somehow interferes with the observer's actual account of the object. Therefore objects which are more accessible are overestimated as FECDOs while object which are less accessible are most likely be considered ICDOs. If this assumption was completely correct, this would suggest that for the objects which have a higher accessibility (e.g. banana or table) all observers should have selected theses objects as FECDO independent of their actual experiences. On the other hand, objects that are less accessible all observers should have identified this object as ICDOs.

However as the data clearly demonstrates this was not the case. Furthermore because observers was given as much time as they wanted to give a response, accessibility may have a little to no influence on observers responses. Take for example a table, while it is possible that a table may be more accessible than an ottoman within the furniture category, one would not doubt that a table is frequently experienced, especially if we consider that the sample size was composed of university student who I would argue actually do frequently see a table, be it consciously or unconsciously, on a day to day basis. Another example is the coke logo an object which is considered an extremely accessible when we concern the brand category, less than half of observer selected this object as a FECDO. Wheat then could be influencing observers' responses and how does this contribute to the overall aim of this thesis? This question will be explore at the beginning of chapter 5.

5 Chapter 5

The effects of correct non prototypical colours on object representation

5.1 Introduction

The representation for CDOs, which primarily includes their typical hue, observed in the study conducted by Naor-Raz and Tarr (2003), has been shown to influence the colour appearance and colour perception of these objects as well as the colour perception of non-CDOs. The same effect was observed in the first part of experiment 1, relating to these objects' representations. For example when observers were presented with true (not potential) CDOs in their achromatic versions and instructed to recover their typical hue, the mental representation of each object's which included their typical hue, that is, the CDO's prototypical colour, was quickly activated. As a result of this activation, observers were quickly able to discount the atypical hues (squared colour patches) which were not a part of these objects' representation and thus selected the typical hue associated with the presented CDO (see section 4.28 and Figure 4.29 for more).

It is, however, still an open question whether the representation of CDOs, include CNPs, and if so, on what level and do they influence the human observer's ability to identify these objects' typical hue or typical hue category. For example if we are to agree that the ability to move or direct the motor system in relation to the visual information presented in the physical world is what distinguishes the mammalian species from other organisms like, for example, plants, allowing members within this group to escape predators and find food and mates, it appears that a representation of, for example, an unripe (green), ripe (yellow), and overly ripped (brown) banana is information which intrinsically must be represented at some level of the object, allowing human observers the ability to move towards the object at a greater efficiency.

5.2 Revitalizing Hering's actual position

"The memory colour (information included on the visual domain) of an object need not be rigorously fixed but can have a certain range of variation depending on its derivation"- Hering (1964, pg.29). When we consider an object's colour, as illustrated by Hering's quote, we should leave open the possibility that a given CDO may be associated with a range of hues either on the visual domain or in other domains – conceptual or lexical, thereby forming a much more dynamic representation of the object. Moreover such formation also Hering's quote suggests may be dependent on the context in which the object's typical hue was initially derived (or learned). Furthermore it should not be a surprise that when we consider the appearance of a given CDO in experience, it naturally appears in more than one hue, leaving room for the possibility of there being more than one memory colour (or a much more dynamic representation) for that particular CDO.

5.2.1 Unpeeling observers' phenomenological responses[17]

In the phenomenological experiment conducted in chapter 4, out of all the CDOs identified, the banana, table and leaf were most likely to be reported as objects frequently experienced on a day to day basis by most of the observers. The other CDOs were more likely to be reported as objects which do not constitute a high percentage of the objects in their day to day visual environment. Why is this? The answer could be as follows - because a banana, leaf and a table appear in hues additional to their typical hue, when asked to report how often they visually experience these objects on a day to day basis, observers typically browsed through the hues associated with these objects (whose range is wider when compared to the other CDOs- ICDOs), eventually causing them to overestimate their day to day experiences with these objects. Another explanation could be that because these objects naturally occupy a high number of areas the observer typically inhabits, the opportunity to experience these objects increases (e.g. for the typical student, a table is presented in the classroom, dormitory, or library), causing observers to overestimate their actual experience with the object. The third option could be a synthesis of the two possibilities, a position this thesis supports and directly argues is the reason why objects, independent of these accessibility, per observer, were reported as either a FECDO or ICDO.

When observers were instructed to judge the presented stimulus and indicate how often they visually experienced it on a day to day basis", observers before selecting a descriptor asked themselves a different question which resembles the following question: in my own immediate environment where I often inhabit, where do I normally travel on a day to day basis and does this object normally occupy these environments? Thus in the case when a given observer perceives the presented object as that which prototypically occupies the observer's actual day to day environments the observer naturally report the presented object as frequent even if they actually do not experience the object on a day to day basis. In the event when the presented object did not appear to prototypically belong in the observer's day to day environments the observer often reported the presented object as an infrequent object.

To further support this rationale, take for example a study conducted by Brewer & Treyens, (1981). In this study observers were briefly presented an environment or context (e.g. professor's office), shown a list of objects and asked to select the objects they saw in the presented context. This list of objects included objects that were actually presented and those which were not presented in the context at all. They found that observers generally selected objects not based on the actual contextual presentations but based on whether they felt the object naturally belonged in the presented context. For example while there were no books presented in the professor's office, observers typically reported that they saw books in the office. Moreover this study is just another example suggesting that in some cases certain objects have a strong object-context conjunction and because of this, how observers recover their actual experiences with these

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[17] By asking observers to recover their lived experiences with respect to a given object does not mean that the responses observers give are factual and therefore treated as such. What is factual is not the responses themselves but the perception of factuality observers' associate with their experiences which somehow modulate the recovery of their actual experiences. What the researcher must then do is unpeel the layers which make up an observers responses in order to recover patterns which can be used to further understand how a given phenomenological state can potentially influence perception as a whole.

objects can significantly be effected. In light of this revelation, how does this tendency to overestimate ones actual experience effect a given object's representation?

5.2.2 Connection subjective responses to object representation

The context in which an object's colour is acquired varies from object to object. For some objects, because of their natural presentations, the colour is acquired in a linear manner as the colour of these objects remains constant over time. However it should be clear that for most of the objects even CDOs which occupy the human observer's physical world, the accusation of their colours is not as straight forwards and is intrinsically dependent on given context. For example in the summer the colour of a leaf is green, in the fall its colour becomes yellow or orange while in the winter is often presented in a dark brown colour. Thus when a leaf is experienced in these colours, human observers are not surprise but are in fact able to activate a much more dynamic representation of the object. In others words, the activation of an object's context or environment, similar to the FECDOs, indirectly activates a much more dynamic representation of these objects' colours. Thus it should be of no surprise that most of the objects phenomenologically identified as FECDO in principal appear in more than one hue. Moreover, to test whether these objects representation are much more dynamic than ICDOs, using the object Stroop decision-time task similar to the one in Naor-Raz and Tarr (2003) study, the CNPs for the nine CDOs were measured, in order to investigate for the first time, whether these CNPs, namely those associated with FECDOs would interfere as observers attempt to recover the typical hue or typical hue category associated with these objects.

5.3 Observers

Each observer had at least four days in between the first and second experiment. Observers who came on Day 1 to participate in the first experiment came in on Day 5 to participate in the main experiment, and so forth. More importantly, the same twenty-four observers who participated in the first experiment participated in the main one. Observers were tested again for normal colour vison, using the Ishihara colour plates. The colour plates were presented on the computer monitor same as the stimuli during the course of the experiment. Note that the choice to present the Ishihara colour plates on the computer monitor is due to the fact that the colour palate's reflectance on a real surface may affect observers colour response. After the completion of the study, observers were debriefed and received £5 for their participation.

5.4 Apparatus

The same gamma corrected computer monitor with the same specification used for the experiment 1 was used for the main experiment. The only difference was the gamma associated with each video voltage channel - $R^{\gamma}, G^{\gamma}, B^{\gamma}$ - which changed from day to day (see section 4.3.1 for gamma associated with each testing days - $R^{\gamma}, G^{\gamma}, B^{\gamma}$). Note that the luminance of the monitor was kept constant at a luminance value of 23cd/m^2. The entire experiment was written in MatLab with the Psychophysics toolbox-3 extension (Brainard; 1997; Pelli, 1997; Kleiner et al, 2007).

5.5 Stimuli presentation

Nine outlined drawings of CDOs converted into achromatic versions were used in this study. Depending on how the observer rated each CDO in the second part of the first experiment, the object was designated as either FECDO or ICDO. The surface of every single object was homogenously presented and specified using the following L*a*b* values: L= 51, a*= 0, b=0. This neutral specification inhibited any sort of priming effect. Each trail could contain either a FECDO or ICDO which were always randomized. Therefore each trials did not need to be counterbalanced by using another groups of participants. Each object was 13.9 deg x 13.6 deg visual angle in size. The eight universal basic colour categories – red (L*= 53, a* = 80, and b*= 67), green (L*= 87, a* = -86, and b*= 83), blue (L*= 32, a* = 79, and b*= -107), yellow (L*= 97, a* = -21, and b*= 94), purple (- L*= 60, a* = -98, and b*= 60), grey (53, a* = 0, and b*= 0), orange (L*= 74, a* = 23, and b*= 78), and brown (L*= 37, a* = 49, and b*= 30) were also used in this study. As it relates to writing, each hue category was written in Times New Roman small case font in a size 36. Each stimulus and hue category was presented on a neutral background with the following L*a*b* values: L= 0, a*= 0, b=0. The presentation of each stimuli and hue category was completely randomised.

5.6 Procedure

There was a total of four conditions – name neutral, colour neutral, name Stroop and colour Stroop. The condition order for each observer was randomized. Each of the nine CDOs presented was presented four times, making for a total of thirty-six trials for each condition. In a completely dark room, at the beginning of each trial for every single condition, observers were instructed to place their chin on chin rest located 51 cm away from the computer monitor. Observers were then asked to read the instructions for the experiment out loud. After this, observers were asked to explain the instructions back to the experimenter in order to ensure that the observers understood the task. After an adaptation presentation of 1000ms, a fixation presentation was presented for 500ms, followed by a mask presentation which lasted for 50ms and immediately after by a presentation of one of the nine CDOs, lasting exactly 1000ms. After the presentation of one of the nine CDOs, the word pair of stimuli was presented (see Figure 5.2 for an illustration of the general presentation for each condition). Word pair selection and decision-time score for each stimulus was immediately recorded on separate text file in MatLab.

CDOs	**Typical**	**CNP1**	**CNP2**	**CNP3**	**CNP4**
Banana	**Yellow**	**Green**	**Orange**	**Brown**	**Red**
Leaf	**Green**	**Orange**	**Yellow**	**Red**	**Brown**
Table	**Brown**	**Grey**	**Orange**	**Green**	**Blue**
Strawberry	**Red**	**Purple**	**Orange**	**Brown**	**Green**
Fire Extinguisher	**Red**	**Orange**	**Green**	**Blue**	**Grey**
Christmas tree	**Green**	**Grey**	**Red**	**Blue**	**Yellow**
Coke logo	**Red**	**Orange**	**Purple**	**Yellow**	**Grey**
Broccoli	**Green**	**Orange**	**Purple**	**Brown**	**Grey**
Cherry	**Red**	**Purple**	**Orange**	**Brown**	**Green**

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Table 6.3: The range of hues associated with frequently experienced colour diagnostic objects. In theory, infrequent colour diagnostic objects do not have additional hues in which these objects are presented in when experienced. For these objects, the colour of its secondary surface regions was selected as its additional hues. For the infrequent colour diagnostic objects which do not have clear secondary surface regions, colours which are perceptually close to the hue were selected as its additional hues (e.g. cherry). Each of the additional hues was presented with the typical hue only once in each condition.

5.6.1 Name neutral condition[18]

For the name neutral condition, the name of the typical hue associated with the presented CDO was orthographically presented, with its letters written in grey ink. Four inches away, the CNP hue also associated with the presented CDO, was orthographically presented, with its letters also written in grey ink. Observers' task was to select, as fast and as accurately as possible, the typical hue's colour name.

For the ICDOs the following is expected: if the typical hue is encoded in the visual domain of the object, this hue should be automatically activated thereby successively activating information on the conceptual and lexical domain. This in turn facilitates observers search for the typical hue's colour name. Thus during the orthographically presentation, observers should easily be able to recover the objects' typical hue's colour name with great ease. For the FECDOs the following is expected: if a CNP hue is also encoded in the visual domain of the object, this hue should compete for activation (i.e. activation of the typical and CNP hue). Despite the competition, the information on the conceptual and lexical domain should be successively activated. Due to the competitive nature experienced on the visual domain, observers must actively direct their attention towards the object typical hue's colour name and not the CNP hue's colour name which are both included on the conceptual and lexical domain of the object. This directing of one's attention should influence to a small degree, how quickly observers are able to recover the typical hue's colour name associated with the presented object. However if the CNP's hue colour name is only encoded on the conceptual and lexical domain of the object, while only the typical hue is encoded on the visual domain, this should lead to the activation of the object's typical hue which is successively followed by an activation of the conceptual and lexical domain. However during the orthographically presentation, as observers began to search for the typical hue's colour name, the CNP's hue colour name also concluded on the conceptual and lexical domain should significantly interfere and thus effect how quickly observers are able to recover the prototypical hue's colour name.

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[18] As it is the case for all of the conditions, the position of each orthographic stimuli presented on the right or left side of the visual scene for each trial was completely randomized. During every orthographic presentation in all conditions, the presented CDO's typical hue or the name of the hue was always presented with one of the four CNP hues or the name of the hue depending on the condition.

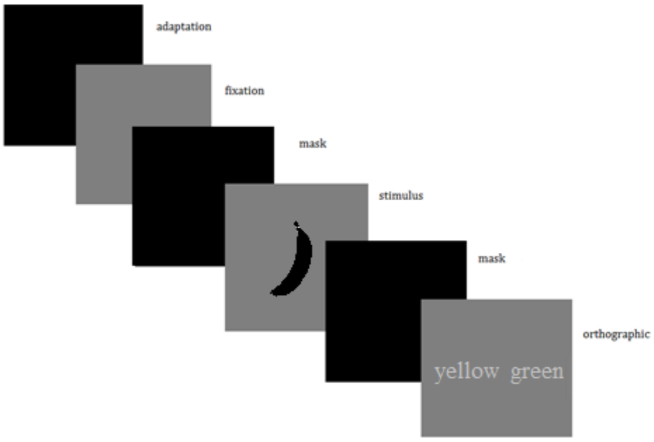

Figure 5.2: General presentation sequence for each name neutral condition for a banana.

5.6.2 Colour neutral condition

For the colour neutral condition, the name of the typical hue associated with the presented CDO was orthographically presented, with its letters written in its typical ink colour. Four inches away, the CNP hue also associated with the presented CDO, was orthographically presented, with its letters written in grey ink colour. In this condition, observers' task was to select, as fast and as accurately as possible, the typical ink colour associated with the presented object.

For the ICDOs the following is expected: if the typical hue is encoded in the visual domain of the object, this hue should be automatically activated thereby successively activating the conceptual and lexical domain of the object. However in order to quickly recover the typical ink colour, observers must maintain the typical hue which was initially activated on the visual domain. This task not only becomes difficult because of the successive activation of the information included on the conceptual and lexical domain but also due to habitual reading which prompts the brain to automatically read presented word which requires little to no directing of one's attention (Stirling, 1979). Therefore the mere presentation of colour names along with having to maintain the typical hue which was initially activated on the visual domain should influence to a small degree, observers ability to recover the correct response. For the FECDOs the following is expected: if a given CNP hue is also encoded in the visual domain of the object, this hue should compete for activation on the visual domain. This is then followed by a successive activation of the conceptual and lexical domain of the object. Because the task requires the recovery of the typical ink colour, the competitive nature experienced on the visual domain (i.e. activation of the typical and CNP hue) is not reliable. Therefore observers must quickly discount this information, and rely on the information included on the conceptual and lexical domain, which is encouraged by the habitual reading effect, to help facilitate a slightly slower selection of the correct response. In the event when the CNP's hue colour name is only encoded on the conceptual and lexical domain of the object, while only the typical hue is encoded on the visual domain. This should also lead to the successive activation of information included on the conceptual and lexical domain. However in this case the initial activation on the visual domain is much more useful and thus must be actively maintained. Equally important, during the orthographic presentation, is discounting the conceptual and lexical activation due to the fact that the CNP's hue colour name is encoded on this domain. Discounting this information is further made difficult due to the habitual reading effects which in all should significantly interfere with observers decision-time scores.

Figure 5.2: General presentation sequence for each colour neutral condition for a banana.

5.6.3 Name Stroop condition

In the name Stroop condition, the name of the typical hue associated with the presented CDO was orthographically presented, with its letters written in CNP ink colour. Four inches away, the CNP hue also associated with the presented CDO, was orthographically presented, with its letters also written in presented object's typical ink colour. Observers' task was to select, as fast and as accurately as possible, the name of the typical hue.

For the ICDOs the following is expected: if the typical hue is encoded in the visual domain of the object, this hue should be automatically activated thereby successively activating the information on the conceptual and lexical domain of the object. This later facilitates observers search for the typical hue's colour name in the orthographically presentation. As observers attempt to recover the objects' typical hue's colour name, there should be a Stroop interfere (or effect), as the correct responses are written in an ink colour inconstant with its colour name. Thus the successful recovery of the correct response requires discounting the Stroop effect which should influence observers' decision time. For the FECDOs the following is expected: if CNPs hues is also encoded on the visual domain of the object, this hue should compete for activation on the visual domain (i.e. activation of the typical and CNP hue), while a successive activation of the information encoded on the conceptual and lexical domain should occur. Because of the competition on the visual domain observers must actively favour and in turn shift their focus to the object's typical hue colour name and not the CNP hue colour name. On top of this, observers must also try to discount a Stroop effect all leading to a significant delay in observers'' decision time scores. If the CNP's hue colour name is only encoded on the conceptual and lexical domain of the object, while the typical hue is only encoded on the visual domain there should also be a successive activation of information on the conceptual and lexical domain. This should facilitate observers search for the typical hue's colour name. However not only should there be a Stroop effect but inference of the object's CNP's hue colour name which is included on the conceptual and lexical domain should in principle cause an even stronger Stroop effect.

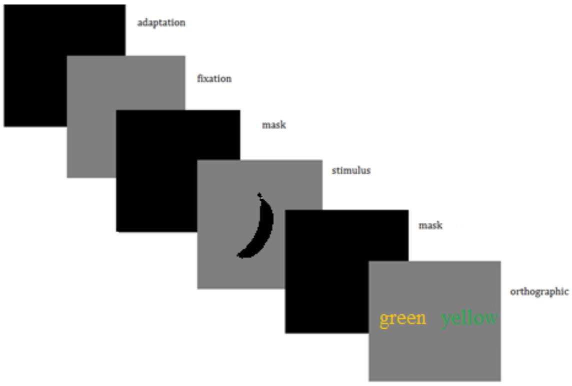

Figure 5.2: General presentation sequence for each name Stroop condition for a banana.

5.6.4 Colour Stroop condition

In the colour Stroop condition, the name of the typical hue associated with the presented CDO was orthographically presented, with its letters written in CNP hue's ink colour. Four inches away, the CNP hue also associated with the presented CDO, was orthographically presented with its letters written in presented object's typical ink colour. However in this condition the task of observers' task was to select, as fast and as accurately as possible, the typical ink colour associated with the presented object.

For the ICDOs the following is expected: if the typical hue is encoded in the visual domain of the object, this hue should be automatically activated successively followed by the activation of information on the conceptual and lexical domain. Because the task requires the recovery of the typical ink colour, observers must maintain the typical hue which was initially activated on the visual domain while simultaneously discounting the information activated on the conceptual and lexical domain which will be made difficult by the habitual reading effect. Finally observers must also discount a Stroop effect and thereby select the correct response which will always be presented in the incorrect colour name – CNP hue's colour name, ultimately slowing down observers' decision time scores. For the FECDOs the following is expected: if CNPs hues is encoded in the visual domain of the object, this hue should compete for activation (i.e. activation of the typical and CNP hue) thereby successively activating information encoded on the conceptual and lexical domain of the object. Because of the competitive nature of the information experienced on the visual domain is not reliable, observers must quickly discount this information, and rely on the information included on the conceptual and lexical domain which is further encouraged by the habitual reading effect, in order to help facilitate the selection of the correct response. During this facilitation observers must not only discount a Stroop effect but also select in the incorrect colour name –

CNP hue's colour name; having to do all this should significantly slow down observers' decision time scores. If the CNP's hue colour name is encoded on the conceptual and lexical domain, while the typical hue is encoded on the visual domain this should lead to the successive activation of information included on the conceptual and lexical domain. Keeping mind the task at hand, observers must first discount activation of information included on the conceptual and lexical domain and actively maintain the initial hue activation of the object' typical hue. During the orthographic presentation, there should be a habitual reading effect in which the CNP's hue colour name encoded on the conceptual and lexical domain should not only interfere with observers' responses but also encourage a stronger Stroop effect. Thus in order for observers to select the correct responses observers must discount a Stroop effect and in turn select the incorrect colour name – CNP hue's colour name; having to do all this should also significantly slow down observers decision time scores and in some cases encourage incorrect responses.

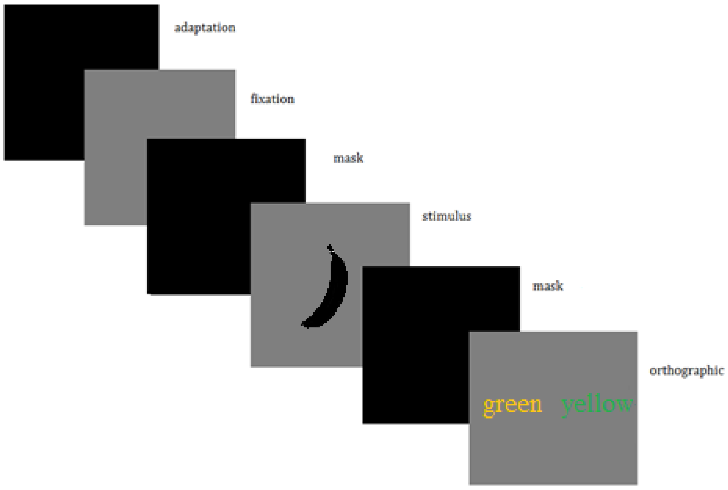

Figure 5.2: General presentation sequence for each Colour Stroop condition for the banana.

5.7 Data Analysis

5.7.1 Name neutral condition

Across all observers and conditions there was a total of 3456 individual decision-time scores, this means that there were 864 individual decision-time scores for each condition. For each condition, FECDOs and ICDOs phenomenologically described by observers in the experiment 1 was assigned the numerical value of 1 and 0 respectively. For name neutral condition after omitting the incorrect responses – 19 FECDOs and 15 ICDOs there was a total of 830 individual decision-time scores remaining.

Because observers' responses could be based on guessing or mouse errors, or misunderstanding of the task along with a host of factors including participant characteristics (e.g., complexity of stimuli, age, intelligence), coupled with the elusive nature of reaction time literature, with respect to the lower and upper limit decision time values, mock participants were used to establish cut off values in this condition as well as the other conditions (i.e. colour neutral, name Stroop and colour Stroop). In order to establish the lower limit value mock participants were instructed to perform the task highlighted above for each condition with the correct responses highlighted by an arrow pointing towards the correct response. Overall, the average decision-time scores was never below 200ms. In order to establish a higher limit value, the same mock participants were used. However this time mock participants were forced to shift their attention to both colour names included in the orthographic representation and only then were they allowed to pick the correct response which was also highlighted by a appointed arrow. Overall no decision-time scores went above 2000 ms.

Furthermore after omitting decision-time scores less than 200ms or above 2000ms - 3 FECDOs and 2 ICDOs, there was a total of 825 individual decision-time scores remaining. For the FECDOs average decision-time score[19] was .588 sec (588 ms) with SE of .025, while for the ICDOs average decision-time score was .510 sec (510 ms) with SE of .039. While a two-way ANOVA on decision-time scores would had been appropriate if there was a need to control for an order effect, however in these experiments the presentations of objects were randomized in each condition as well as the condition presentation order (colour neutral, name Stroop and colour Stroop). Thus a within-subjects one-way ANOVA was performed in order to investigate if the difference between average decision-time scores were significant. The ANOVA revealed no significant difference between the decision-time scores with $F_{1,23}= 3.81$, with $p>0.05$.

5.7.2 Colour neutral condition

For colour neutral condition after omitting the incorrect responses – 24 FECDOs and 18 ICDOs there was a total of 822 individual decision-time scores remaining. Decision-time scores less than 200ms or above 2000ms – 24 FECDOs and 10 ICDOs, was later omitted leaving a total of 788 individual decision-time scores remaining. FECDOs yielded an average decision-time score of .726 sec (726 ms) with SE of .039, while ICDOs yielded an average decision-time score of .623 sec (623 ms) with SE of .053. A within-subjects one-way ANOVA was performed revealed a significant difference between the decision-time scores with $F_{1,23}=$ 4.89, with $p<0.05$.

5.7.3 Name Stroop condition

For name Stroop condition the incorrect responses (72 FECDOs 80 ICDOs) were omitted leaving 712 individual decision-time scores. Next decision-time scores less than 200ms or above 2000ms (27 FECDOs 18 ICDOs) were omitted leaving 667 individual decision time scores. With respect to the average decision-time scores FECDOs yielded an average decision-time scores of .861 with an SE of .043, while the ICDOs yielded an average decision-time scores of .810 with an SE of .066. Following this a within-subjects one-way ANOVA was performed which revealed that the different between reaction time scores was not significant with $F_{1,23}= .864$, with $p>0.05$.

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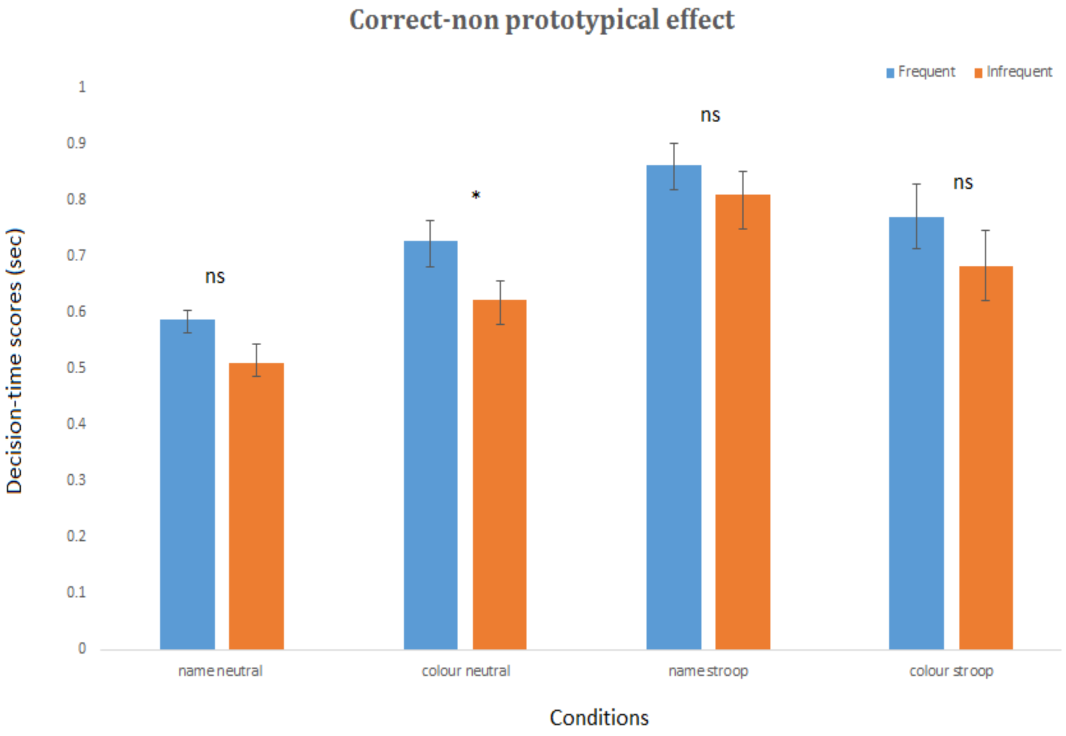
[19] By omitting decision-time scores, the ANOVA is mostly likely going to be effected by the unequal sample size for object type- FECDOs and ICDOs. To control for this unequal sample size, the Type III method was used. As a result of this, instead of using the actual mean which takes into account the unequal sample size, the harmonic mean (or unweighted mean) was used in order to detect if there is in fact a mean effect of object type

5.7.4 Colour Stroop condition

For colour Stroop condition 311 decision times scores (169 FECDOs 142 ICDOs were omitted which left 553 individual decision-time scores. Following this, 67 decision-time scores (40 FECDOs 27 ICDOs) were omitted as they fell under 200ms or above 200ms. This left a total of 486 individual decision-time scores remaining. FECDOs yielded an average decision-time of .769 (769ms) with a SE of .065, while ICDOs yielded an average decision-time score of .682 (682ms) with a SE of .068.Finally a within-subjects one-way ANOVA was performed which revealed that the different between reaction time scores was not significant with $F_{1,23}$= .563, with p>0.05.



5.4: Evidence for the effect of correct-non prototypical colours on frequently experienced colour diagnostic objects. On the Y axis is the decision-time in sec with its associated standard error for each object type in each condition. On the X axis is each of the experimental conditions, while the yellow bars represent the frequently experienced colour diagnostic objects and the blue bars represent the infrequent colour diagnostic objects.

5.8 General discussion

The overall aim of this thesis was to investigate whether the object representation of CDOs, which primarily includes these objects' typical hue, also included any information about these objects' CNP. Based upon previous studies on CDOs, it is quite clear that the representations of CDOs, which includes their typical hue, does in fact modulate the colour appearance of a given object, significantly influence the colour perception of non-CDOs, and aid during object and scene recognition (Oliva & Schyns, 2000). However, the representation of CDOs, if the only information it represents is the prototypical colour of these object as previous studies have suggested, is limiting and not dynamic enough deal with these objects in atypical viewing conditions. As it has been argued throughout this thesis, particular in Chapter 4 and 5, there are CDOs – FECDOs which appear in the physical world in more one than one hue. Even today, these objects make up a high percentage of the objects surrounding the human observers (e.g. traffic signals and signs) as the phenomenological results in the second part of the first experiment reported in this thesis suggest. Ultimately this thesis provides evidence that for certain groups of familiar objects, their CNPs are included on the conceptual and lexical domain, additional information human observers are able to use as they quickly attempt to recognize these objects in atypical perceptual conditions.

5.8.1 FECDO incorrect responses

In the main experiments, with respect to the CNPs, results demonstrate certain behavioural patterns. Firstly, it is clear observers had a much more difficult time recovering the typical hue or the typical hue colour name for FECDOs across all conditions as more FECDOs were discarded because of an incorrect responses. Also while not all average decision-time score differences were significant FECDOs decision-time scores for all conditions were always slower than ICDOs decision-time scores. This suggests that observers may have had to process or discount more information as they attempted to recover the typical hue or typical hue colour name for the presented FECDOs when compared to ICDOs.

5.8.2 Conceptual and lexical domain

Pertaining to whether or not CNPs are include in the representation of familiar objects, the ANOVA which compared the average decision-time difference for each condition revealed, surprisingly, for the colour neutral condition a statistically significant difference. This difference suggest that CNPs hues may not be encoded on the visual domain of the presented objects, but that the CNPs colour name are included on the conceptual and lexical domain of these objects. For example it appears that for the ICDOs there was an automatically activation of these objects' typical hue which successively activated these objects' conceptual and lexical domain. However observers were able to maintain the initial visual activation of these objects which lead to the recovery of the typical ink colour with great ease. However in the case of the FECDOs it appears that the CNP colour name were encoded on the conceptual and lexical domain of the object. Thus the mere presentation of CNP colour names drew the attention of observers not solely because of habitual reading effect or the fact that the colour name was written in a grey ink colour and thus highlighting the colour name from the correct response, but because of an activation of CNPs intrinsically include on the conceptual and lexical domain which may have been indirectly activated due to the object's contextual association.

5.8.3 Difficulty of task

With respect to the task observers had to perform within a given condition, results suggest two things. Firstly it appears that the task was very difficult for most observers and this is clear as from the name neutral, colour neutral, name Stroop to the colour stoop condition, observers began to give more incorrect responses. This also implies that observers began to guess and were unable to use any reliable strategy as they attempted to recover the correct response for a given trial. Secondly it seems that observers had a greater difficulty with recovering the typical hue of the object when compared to the object's typical hue category. This could be due to the fact that after the activation of these objects' typical hue which successively activated information on the conceptual and lexicon domain, observers had a hard time maintaining the initial typical hue activation and discounting the information included in the conceptual and lexical domain especially when the object was a FECDO.

5.8.4 The implications of results

When we take into account the results discussed in this thesis, several question arise? The first pertains to early learning of the typical hue associated with a given objects. Take for example the study conducted by Schyns et al (1997). In this study, observers were presented novel stimuli, that is, stimuli that do not exist in everyday life. Observers were later instructed to describe the different features of the presented stimuli. Results demonstrated a change in observers' perceptual appearance of the object as observers often described the novel stimuli with respect to their learning experiences. Results further suggest that human observers generally gain information about the world through previously obtained experiences and in turn use these experiences when constructing a final perception of objects in the physical world. Therefore if we combine the results highlighted in this thesis and the study mentioned above, it very possible to see that objects whose CNPs are known by a given observer and thus included in the representation of the object, may be due to the fact that the initial acquisition of these objects' typical hue are much more dynamic when compared to other sets of objects . In other words if it is possible to understand the same object in a completely different way with respect to its colour, then surely it is equally possible to synthesis this both types of information into one for a given object, especially if this information can reduces any potential novelty.

The second point is with respect to the role of CNPs on colour perception and the recognition literature. If it is the case that CNPs is included on the conceptual and lexical domain of certain familiar objects as this thesis suggests, does this information effect the colour appearance of a given object? In other words if asked to make achromatic a green banana will the same effect observed with a yellow banana be observed as in the case of the study conducted by Hansen at al (2006)? Secondly are CNPs also strong enough to calibrate the perception of non-CDOs as demonstrated in study conducted by Mitterer & Ruiter (2008)? With respect to the recognition literature, do CNPs objects help in scene recognition and object recognition similar to prototypical colours as demonstrated in the study conducted by Schyns et al (1997)? These questions are all questions that future studies should direct their attention if we are to understand the perceptual nature of these objects and most importantly if we are to understand the adaptive role of these objects on emergence of primate colour vision.

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7 Glossary

Correct non-colour prototypical colours –

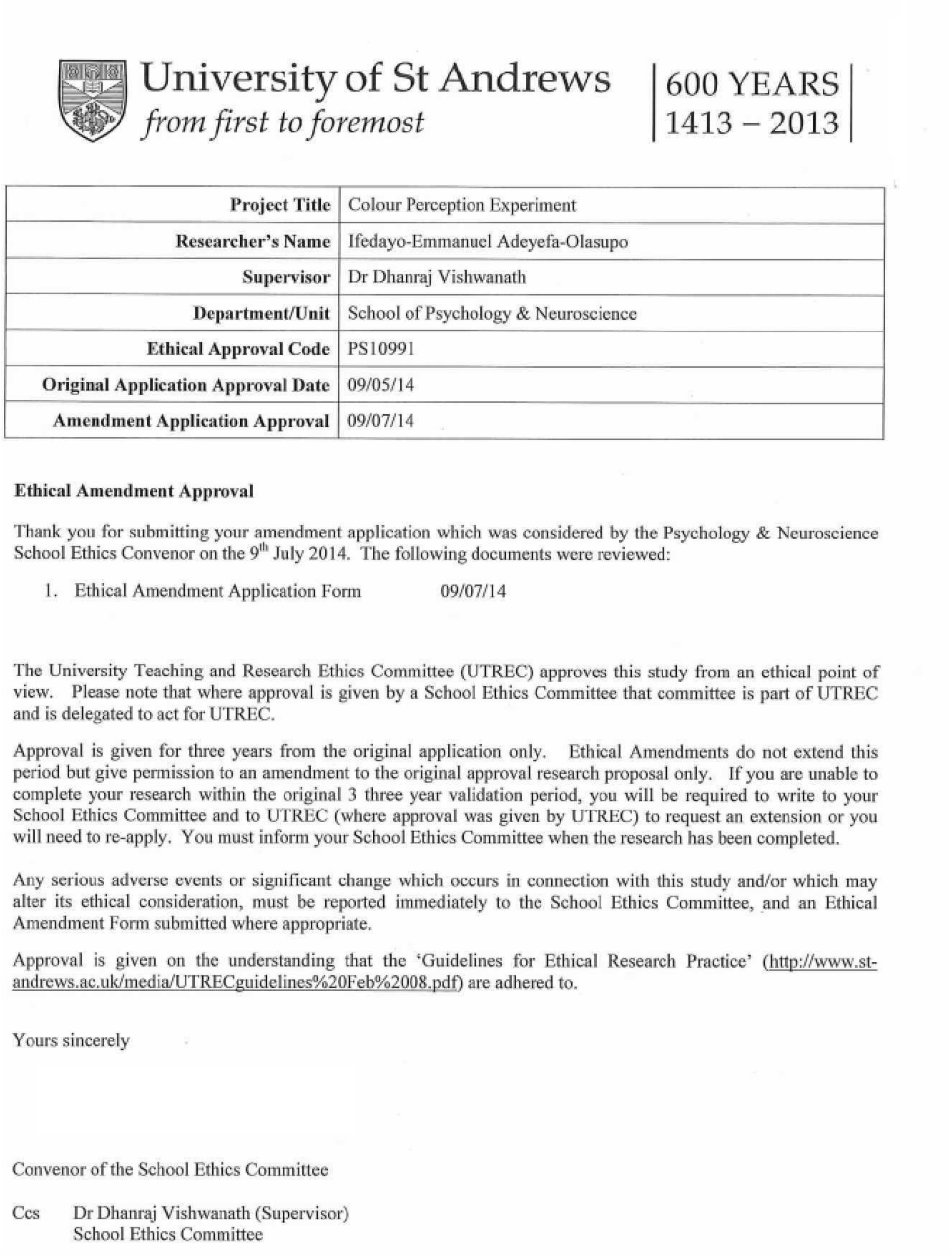
Secondary colours familiar objects – artificial and natural are naturally presented in which generally falls within the (M)-, and long (L) – colour spectrum (cones which are extremely critical to colour vison) or in some cases a combination of two distinct spectral colours (e.g. green + red = yellow); these colours: i. modulate the strength of colour diagnosticity associated with a given objects and ii. carry additional information which can be used to guide the primate movement towards or away from the object

Infrequent colour diagnostic objects:

Infrequent colour diagnostic objects can either be high or low colour diagnostic object which are a subset of familiar objects are objects humans subjectively report as objects they do not frequently experience on a day to day basis (i.e. < 4 on the experiential scale) when compared to other sets of colour diagnostic objects. They may also, like frequently experienced colour diagnostic objects, represent a prototypical example of a given class of objects but generally have a fixed object-colour association with little to no correct non-prototypical colours. Giving the infrequent status to these objects is driven by a combination of both variables.

Frequently experienced colour diagnostic objects:

Frequently experienced colour diagnostic objects can either be high or low colour diagnostic object which are a subset of infrequent colour diagnostic objects humans subjectively report as objects they frequently experience on a day to day basis (i.e. => 4 on the experiential scale) when compared to other sets of colour diagnostic objects. While observers may in fact frequently experience these objects on a day to day basis, there can also be a more defining variable driving these phenomenological accounts which causes observers to overestimate their actual experience with that very object. This defining variable could be that the object is easily recalled from the category it belongs to, has a fixed object-colour association, appears in more than a single typical colour, or a combination of the three.



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1413 – 2013

Project Title	Colour Perception Experiment
Researcher's Name	Ifedayo-Emmanuel Adeyefa-Olasupo
Supervisor	Dr Dhanraj Vishwanath
Department/Unit	School of Psychology & Neuroscience
Ethical Approval Code	PS10991
Original Application Approval Date	09/05/14
Amendment Application Approval	09/07/14

Ethical Amendment Approval

Thank you for submitting your amendment application which was considered by the Psychology & Neuroscience School Ethics Convenor on the 9th July 2014. The following documents were reviewed:

1. Ethical Amendment Application Form 09/07/14

The University Teaching and Research Ethics Committee (UTREC) approves this study from an ethical point of view. Please note that where approval is given by a School Ethics Committee that committee is part of UTREC and is delegated to act for UTREC.

Approval is given for three years from the original application only. Ethical Amendments do not extend this period but give permission to an amendment to the original approval research proposal only. If you are unable to complete your research within the original 3 three year validation period, you will be required to write to your School Ethics Committee and to UTREC (where approval was given by UTREC) to request an extension or you will need to re-apply. You must inform your School Ethics Committee when the research has been completed.

Any serious adverse events or significant change which occurs in connection with this study and/or which may alter its ethical consideration, must be reported immediately to the School Ethics Committee, and an Ethical Amendment Form submitted where appropriate.

Approval is given on the understanding that the 'Guidelines for Ethical Research Practice' (http://www.st-andrews.ac.uk/media/UTRECguidelines%20Feb%2008.pdf) are adhered to.

Yours sincerely

Convenor of the School Ethics Committee

Ccs Dr Dhanraj Vishwanath (Supervisor)
School Ethics Committee