TÉCNICO LISBOA

MSc PROJECT REPORT

Will it Blend?

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Abstract

Nice abstract goes here . . .

Chapter 1

Introduction

Color can inspire, affect your mood, influence your attitude and change your opinion. It has been associated to brands and constitutes a powerful way of creating instant associations in people's mind. It is one of the most interesting subjects of research due to its psychological and physiological complexity and, nowadays, it is impossible to dissociate what you see around from a color: for example, Starbucks® has a strong connection to Green, Target® to Red, UPS® to Brown and Wimbledon Championships® are strongly associated to Purple and Green.

Everything around us produces sensations on us, which will be parsed by our sensorial system based on a set of principles that help our brain build the perceptual world, filled with familiar or non-familiar concepts: by developing a mental process that represents awareness and knowledge of the real world, it aids the creation of mental models and improves responsiveness to different *stimuli*. Hence, it is not only what surrounds us that influences what and how we process information, it is also public opinion, majority and minority behaviors. The tendency is to think that the more acceptance that a given concept or option has, the larger the tendency to absorb behavioral patterns from the majority: but, investigation has been done [MLN69], and it is possible to acquire behavior from a consistent minority, even though we tend to believe that somehow, the minority has not the same credibility as a majority.

As it is stated by Chirimuuta [Chi14], Color is a subjective interpretation of an objective physical *stimulus*, which may differ from person to person. We, as humans, do not equally perceive color: by saying this, it is affirmed that the definition and the interpretation of a colored *stimuli* can diverge depending on the philosophical mindset a person follows. Color has been object of study of different Philosophies and the definitions of this concept can vary from the simplest statement that colors are simple, primitive intrinsic properties of physical objects, to the description that colors are subjective properties projected onto object's physical surface and light-sources. The perception of color is even more complex if you consider that there are underlying structures whose reason to exist is to process color information: however, this structures may not be present in every human visual system, which creates Color Vision Deficiencies that have to be tested out.

A curious fact is that even if we would consider a perfect world, where no one would have a color vision deficiency and everyone followed the same philosophy, it would be possible to find someone which could distinguish different colors than us: color perception is influenced by cultural patterns and the environment in which we evolved as a specie; some tribes in Africa are able to tell more differences between different shades of green that any other color, since the need to distinguish beneficial from maleficent plants urged and was passed through evolutive generations.

Hence, creating colors standards was more than a need. The formation of color is based on the principle of combining a red, a green and a blue light source, which will determine the color perceive by the brain. As it is known, the human visual system can only perceive light from a well defined wavelength range (from under 400 nanometers until 750 nanometers, approximately) and this, in the long run, determines the spectrum of colors which is human perceivable. This range happens to be defined in the CIE 1931 Color Space, which comprise all color sensations a human can perceive, standing out as standard for other color spaces; this color space originates a horseshoe-type of diagram, in which different color gamuts can be mapped onto. Examples of Color Models that generate interesting color gamuts are the RGB, the HSV/HSL and the CMY(K), among many others. However, combining colors can produce different results depending on the media the color is represented, which will ultimately affect the choice of using a given color system: inked colors tend to mix into darker colors, while lighted colors tend create lighter results when combined, forming white light.

Color is, nowadays, remarkably used as a powerful tool to convey information: it is used on statistical graphics, cartographical data, information visualization and developers are eager to use color in their interfaces to create a better User Experience - when accompanied of a nice Color Scheme. Particularly, when showing data variables on a graphic, it is commonly associated to each variable a color and relationships between them are concluded by observing it. Certainly, it would be useful to combine variables in the same graphic, in a technique of *Color Blending*, conveying exactly the same information but, from a Computer Graphics perspective, in a much prettier and economical way. Nonetheless, there are always bad examples for this technique that yield terrible visualization results, just by not choosing an appropriate color scale or not taking into account the size and shape of the subjects to present.

The technique of *Color Blending* has not been widely exposed and investigated, but some interesting advances have been made yet. It has been investigated if the blending of colors for data visualization [GG14b] would be a proper technique to convey information, so as for Visualizing Social Personal Information [GG14a]. On the other hand, it is important to understand if users are able to perceive different amounts of blended colors [GG14c], which end up representing different values for data variables: would it be counter-productive to show data variables in a blended mode, if the users could not tell which variable had the highest value? If not, how many variables are the users capable to distinguish when blended?

There are some researchers that have developed parallel techniques which make use of Color Blending in different ambits, such as blending colors forming stitched patterns in order to improve the perception of originally mixed colors [UIM03], or methods to create colors that naturally mix without creating confusing colors to user [CWM09].

Even though investigation has been done, there are flaws and situations raised from them that remain to be fully tested and understood. The focus of this research is to take advantage of those loop holes and extensively analyze what comprises the Color Blending field of research.

1.1 Research Goals

The goal of this research is to *study if color blending techniques can be used in an efficient way and, if so, how do we use it to convey information in the most efficient possible way.*

It is important to understand if color is, in fact, a good channel to transport information and to understand how color is perceived by the users. In order to study Color Perception, it is needed a *profound research about color theory*, to review which color spaces and models present a better alternative for the task of representing human perceivable mixtures of colors.

Moreover, it constitutes an interesting topic of research *the extent to which a person can distinguish different amounts of blended colors*, not only when mixing pure colors but also when applying different modifications to color concepts, such as the lightness, luminance or saturation.

To study the aforementioned topics, we intend to test a large number of users which will represent different age groups, cultures and social conditions; at the same time, it will be studied *the way color is influenced by its surroundings and which colors represent a better combination to color usage*.

In the end, if time comes to prove color blending can be used in an efficient way, our main goal is to *create a set of guidelines which prove that color blending can be used to present multiple data variables at the same time*.

Chapter 2

Related Work

In this section, we introduce a review through the topics related to this project. We start by introducing an explanatory view about Perception in its broadest sense, narrowing it down to the particular case of Color Perception. Later, we are going to introduce the theory behind Color Spaces and Models, ending this section with an overview about the usage of Color Blending and the investigation that has been done, to understand the perception on this.

2.1 General Perception

2.1.1 Origin of Perception: Discovery and Definition

Since the 19th century, researchers from experimental psychology, revealed renewed curiosity and aspiration to design an approach to perception and what it brings to the world: how we see things, how we feel them, what does it trigger in our brain, which influence does it have in our social behavior? Perception comprises the process of identifying, interpreting and organizing information acquired via sensorial nervous extremities, in order to understand the surrounding environment of the subject. The Human sensorial system can be described as the vision sensation, olfaction, gustatory, vestibular and somatic sensation. Sensations are low-level neurological events that begin with external *stimuli* reaching receptor cells, but how do sensations become perceptions?

2.1.2 Transforming *stimulus* in Perceptions

Everything around us produces sensations on us, which will be processed by our sensorial system, but there are some steps our brain does without we even notice it, to organize these sensations and *stimulus* into perceptions. There is a set of principles which guides us through the organization of the perceptual world [BN14], from perceptual organization to perceptual depth and distance, motion and, finally, perceptual constancy; they are simple, underlying, truths unconsciously practiced every day.

1. **Figure-Ground Principle:** When looking at a complex subject, your "perception decision center" automatically emphasizes objects apparently more relevant than the background. By doing this, the emphasized part of the subject gains contours: this edges separate the emphasized object, which we call the **Figure**, from the irrelevant background, the **Ground**. For example, as seen on Figure 2.1 when you approach a road intersection the stop sign will become a figure and the ground will be the buildings or other artifacts meaningless to the stop sign.

Figure 2.1: Stop Sign on Road Intersection.[1]

2. **Grouping:** Certain properties of the stimuli lead us to group stimulus together or not, inferring relations among them, in a process more or less automatically. In the very ending of 19th century, beginning of 20th century, the Berlin School of Experimental Psychology became famous for a study driven by several German psychologists which came up with the concept of Gestaltism (origin in the german word *Gestalt*, which means "shape"); in their study, they propose a set of principles that describe how raw sensations are attached to each other by the perceptual system: proximity, similarity and continuity between objects, closure (tendency to fill missing parts of incomplete objects), similar texture, simplicity and common fate (whether the objects are moving on the same direction or not). In the end of 20th century (1999), Stephen Palmer added synchrony principle, common region (*stimuli* located within boundaries are likely to have something in common and are grouped together) and connectedness, to specify *stimuli* connected by other elements. For example, a football team which dresses the same outfit is perceived as a group.

Figure 2.2: "The Marriage of the Virgin" by Raphael[2], 1504.

3. **Depth Perception:** Due to depth perception, we are able to perceive the world in three dimensions. This principle transcribes the ability to perceive distance, through *stimulus* cues:

   - Closer objects block the view of things that are farther away.
   - If we assume two objects are the same size, the object producing a larger image is perceived as closer than the one who which produces a smaller image.
   - More-distant objects usually appear higher in the visual field, than those nearby.
   - The closer two converging lines are from each other, the greater the perceived distance.
   - A reduced clarity helps producing the depth perception: increasing distance usually produces less clarity, whose interpretation is to appear farther and at greater distance. For what is worth, light and shadow also contribute to three-dimension impression.

   An example of this principle is a person who looks tiny and appears high in the visual field, is automatically perceived as being the normal size, but farther away from the observer. Figure

[1] From: http://flic.kr/p/fFkESd. Accessed on 2015/11/04.
[2] From: http://totallyhistory.com/the-marriage-of-the-virgin/. Accessed on 2015/11/04.

is an example 2.2 of a painting which achieves the illusion of depth.

4. **Motion Perception:** Looming is an important optical flow pattern for motion detection: when an image looms (*i.e.* the rapid expansion of the image on the retina), it is automatically perceived as the object moving towards the observer.

5. **Perception Constancy:** Despite changes in the size of the image produced on the retina, it automatically known that the object maintains its size, shape and other characteristics. To visualize this principle, imagine you are the observer and you are seeing a person approaching you: when this person is farther away (but close enough for you to see it), its size is small enough for you to cover the retinal image with your hand; as distance goes by, the retinal image keeps getting bigger and you cannot cover it anymore: However, the observer knows that the person he had visualized before has exactly the same real size, although the retinal image were different sized.

2.1.3 Transforming Perceptions in Familiar Concepts

Now that the *stimuli* are perceived and processed, your brain starts to scrutinize patterns of information and compares them to previous perceptions and familiar concepts. If an analogue memory is already stored in memory, the perception is recognized; once the *stimulus* is identified as familiar, the perception of it will never be the same again. Either recognized or not, the brain can perform two types of processing to create a match between stimulus and stored perceptions:

1. **Bottom-Up Processing:** As in an algorithm, the *stimulus* is firstly decomposed into basic features, which are recombined to create the perceptual experience. These basic features are obtained by specific cells which reside along between the eye and the brain, triggered only when the matching stimulus get to them. This decomposition is very useful in the recognition of shapes or letters and gradients. For example, you recognize a snake because of its features: elongated, legless and they rattle, which perfectly match the perceptual category for "Snake".

2. **Top-Down Processing:** This phenomenon starts from the top, knowledge-based information or concepts before working his way to decompose the *stimulus*. Top-down processing is also known as conceptually-driven processing, since perceptions are conditioned by beliefs, expectations and other considerations: people rely on their knowledge to carry out inferences which help them recognize, for example, patterns. This illustrates how our brain creates schemas, representations of past experiences, guiding new perceptions through the path of processing until it becomes a familiar concept. For example, if you try to walk inside a barely lit division you know well, you can fairly walk without crashing onto something, because the stimulus sent by those objects occur at the location where you would expect them to be.

Perception, as seen, is a mental process that represents awareness and knowledge of the real world; its goal is to help us create mental models about what surrounds us, creating useful information in order to react to different stimuli. On the other hand, sensation has the aim of detecting subjects: it is clear that every part of sensorial system plays an unquestionable role in the act of detecting and perceiving subjects... but how do we see them and acquire intelligence from them?

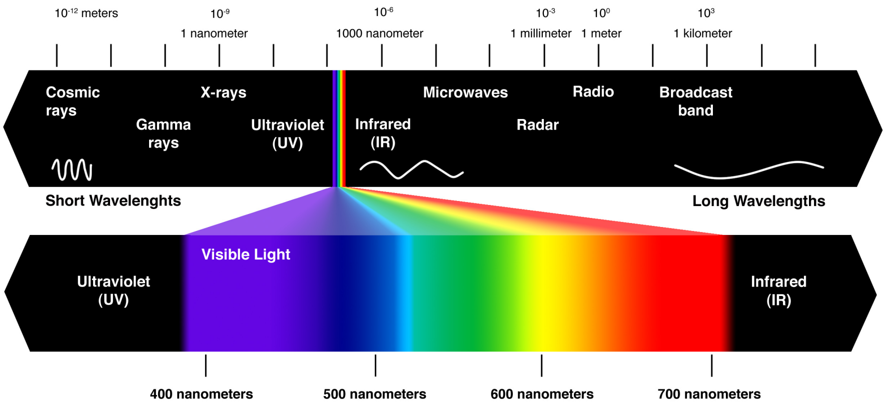

Figure 2.3: Visible Spectrum of Light.[3]

2.1.4 The Human Eye - Part I: From the Cornea to the Brain

The Animal visual system is a direct consequence of evolutionism: it is perfectly adjusted and adapted to the way of living of every animal, we don't hunt like wild animals, but our visual system is prepared to distinguish a wide range of green colors since we evolved as a species surrounded by green vegetation and knowing what to eat was a matter of life or death. The human visual system is adapted to do many things, specially detecting sharpness and color with great precision and sensitivity during the day light and night, although our night vision isn't quite accurate.

Light is electromagnetic radiation, but most of this radiation is invisible to the human eye: it can perceive light from under 400 nanometers until 750 nanometers, as seen on figure 2.3.

When the light strikes an object, depending of the surface's material, it can either: be wholly or partly absorbed, reflected or transmitted; what we perceive as being an object is the light reflected of the surface. The human eye (Figure 2.4), then, decodes light energy into neural activity: the rays enter in the eye through the **cornea**, a curved transparent layer. Then the light reaches the **pupil**, the opening right behind the cornea. The **iris** adjusts the amount of light which enters the eye, by closing the pupil or dilating it (with high level of light, or low, respectively). Next up, the light reaches the **lens**, another curved surface that bends the light rays and projects a sharp image on the **retina**, a surface at the back of the eye. However, this sharp image is inverted, as the light rays from the top of the object are being project on the bottom of the retina, so as the light rays coming from the right side of the object, projected in the left side of the retina. This image is going to be rearranged by the brain.

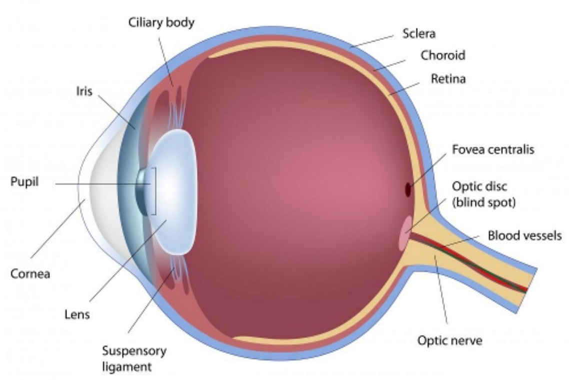

Figure 2.4: The Anatomy of the Human Eye[4]

[3]From: http://www.skepticalartist.com/2013/06/25/claude-monet-and-ultraviolet-light-did-the-master-impressionist-painter-have-uv-supervision/. Accessed on 2015/11/04.

[4]From: http://www.blackandlizars.com/eye-care/eye-health-eye-conditions/anatomy-of-the-eye.aspx. Accessed on 2015/11/04.

In order to be rearranged, the light is conversed in the retina, which contains specialized cells - photoreceptors - that convert light energy into neural impulses, which are send to the brain. There are two main types of photoreceptors: **cones** and **rods**, retinal cells that respond to light due to the absortion of photons in their proteins (This is covered in more depth in section 2.2). Cones are concentrated in the **fovea**, where the light rays entering the lens are focused.

The image is only sent to the brain after the signal generated by the cones and rods is processed also in the bipolar cells of the retina, where visual information begins to be analyzed even before the information leaves the retina. But after all, the brain digests the signals sent has we discussed previously; moreover, as Attneave [Att54] states in its investigation in 1954, a major function of the human perception mechanism is to strip way some redundant information present in the *stimuli*, in order to encode or describe the incoming information in a more economical form, than the one in which it impinges on the receptors. Likewise, sensorial events from different sensory systems may create interdependencies among each other, either in space or in time, or crosscut both; over his life, any individual acquires notions about "what-goes-with what", and, as the author states, we cannot make predictions about anything, based merely on the present visual field, but also depend on previous - and, for that, familiar - visual fields. Even the familiar perceptions and visual fields can be adjusted by the social environment and people around us: we can choose to follow either a majority or minority, construct a mind set or change the way we process perceptions.

2.1.5 Social Behavior

We can study how society and other individuals manage to influence how the information is perceived: in general, we tend to acquire behavioral patterns that a majority of the population already follows. But, if we consider ourselves as a part of the majority, are we influenced by different opinions or social behavior of a consistent minority?

This question was profoundly explored by Moscovici *et al.* [MLN69], whose intention was to perform a study in which they demonstrated the influence of a minority on the responses of the majority. Let us suppose a subgroup of a majority starts to diverge from the repeated mode of response, and this subgroup starts providing an alternative response to the same *stimulus*: this diversity breaks conformity in the group and engenders uncertainty. A minority will not only cause a conflict, but will intensify it if the answer continues to be declared. This is due to the fact that judgements presented by the minority have exactly the same value as majority's opinion.

Moscovici created a laboratorial experiment to observe if the color perception and opinion of the majority was modified by having a minority of two people agreeing on a completely different color. The researchers presented to the group a set of slides containing a color; in each experiment group, they added two subjects who were supposed to consistently agree on the same - different from majority - color. Also, between experiments, they managed to control the light intensity of the room, in order to test the influence of this aspect on the perception. Although there was no discrepant contrast, researchers were able to conclude that the majority agreed more easily with the minority if the lights were slightly dim: this adds an hesitation factor to the majority, since it is more complicated to perceive in a clear way colors.

The most curious conclusion is that the majority considered that the color perception of the minority was not as good as theirs (since they presented a completely different opinion) but still, they perceived them as being more certain of their opinions than themselves; in general, the relative certainty of the majority is weakened with a consist minority, being the minority's opinion true or not.

We have discussed what is a perception: from the very beginning with a *stimulus*, the light that reaches a subject and is reflected through the human eye, inverted and projected in the retina, how we process the information and which mechanisms we do use to create memories and familiar concepts. But one of the most interesting studies one can do is about the human perception of color: do we all perceive color in the same way? How do we construct and organize color? Are we able to create models that describe color in the real world? Which is the influence that our sensations and memories play in the job of color perception?

2.2 Color Perception

2.2.1 Color Philosophy

Looking up for a concrete definition of color is a hard task: there are quite a few ways to perceive color. Color raises serious metaphysical questions[5], concerning the physical and mind reality of it. Color is an important feature of subjects: it allows us to recognize objects, locate them, it fires emotions and behaviors and supports protocols over the world. Probably, the major problem of color has to do with what we seem to know about it, into what physical properties of objects and materials express about them; David Hume defended in 1738 that "(...) Sounds, colors, heat and cold, according to modern philosophy are not qualities in objects, but perceptions in the mind (...)", a highly subscribed dogma. This affirmation describes two important tendencies, the **elimininativism** and the **subjectivism**: the first one is the view that tells physical objects don't have an inherent color associated to themselves, the last one states that color is a subjective attribute of objects. Chirimuuta recently [Chi14] argued about the different mindsets one can have regarding color: its main argument is that Color is a subjective interpretation of an objective physical stimuli and, to justify this statement, he settles a contrast between rival theories of color. Color **realists** accept that colors are indeed physical properties of objects but instantly, two questions arise from this: 1) what really is color and its properties, and 2) do objects really possess those characteristics? With respect to these questions, we can derive even more theories:

- **Primitivism:** Colors are simple, primitive properties physical objects have or appear to have. Colors are intrinsic, non-relational, non-reducible, qualitative properties.
- **Reductive Physicalism:** Colors are complex features, hidden properties of a body which make them appear to have color; they are objective properties of material bodies and, by "hidden", it is meant to require empirical investigation to discover.
- **Dispositionalism:** Colors are perceiver-dependent properties of objects; there are different ways for appropriate perceivers, under appropriate circumstances, i.e. they cause experiences of a certain type in those conditions.
- **Projectivism:** Colors are subjective properties projected onto object's physical surface and light-sources.

[5]"Stanford Encyclopedia of Philosophy: Color", Available at: http://plato.stanford.edu/entries/color/. Accessed on 2015/10/30.

- **Subjectivism:** Colors are subjective features of objects, subjective to experiences or qualities of experiences.

Chirimuuta also compares the Realism against the Anti-Realism, since the metaphysical question "Can we say that objects are actually colored?" is promptly denied, colors do not physically and mentally exist and nothing is, in fact, colored: it is even said that classifying color by its features is an illusion. As the author afirms, his view is close to **Relationism**, a theory which fills the gap between the previous mindsets. To fathom color, we have to consider both the perception and the external *stimuli*, and treat color as the result of this interaction; the task of interpreting color is part of the mechanism of accessing multiple properties of objects, as shape, lightness, composition, *etc.* Colors are, therefore, relational properties, with respect to perceivers and circumstances of viewing.

Regardless of which opinion you support, color has come to be an undeniable point of major interest of studies: from philosophy, to psychology, computer science or statical analysis, color plays a major role in presenting numbers, conveying ideas and spreading information. To endorse this usefulness, different color theories were discovered all along the years and were accompanied by a profound research about the Human eye.

2.2.2 The Human Eye - Part II: Cones and Rods

In section 2.1, the path followed by ray of lights towards our retina was extensively explained. Briefly summarized, part of the projected light on the object' surface is reflected: this light reaches the eye through the cornea, crosses the pupil and is refracted by the lens, coming to a final projection in the back of the eye, the retina. Nonetheless, there are some specialized and important neurons that have the crucial task of capturing and transducing photons: they convert electromagnetic radiation into trigger-signals to be send to the organism.

The photoreceptors can be classified between **Cones** and **Rods**.

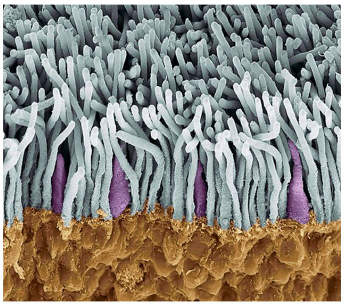

Figure 2.5: Representation of Cones and Rods.[6]

Cones

These cells are responsible for acquiring color vision information, at normal-to-high levels of bright light. They are condensed in the fovea, which is a rod-free zone. By the time of 1990, in a study performed by Curcio *et al.* [CSKH90] it was estimated that in the human retina, the total number of cones ranged between 4.08 to 5.29 million, Cone cells are not important to light detection, since they are not light sensitive; however, color perception is all instrumented by them. They can be seen on figure 2.5 as being the pink colored structures. These cells are named for their shapes and contain chemicals - the photospins - that respond to light: when the light strikes these chemicals, they break and create a signal which will be transferred to the brain. Curiously, there are three kinds of light-sensitive chemicals in cones and they will be providers for the basis of color vision, creating the distinction between the number of cone types: three.

[6]From: http://www.intechopen.com/books/topics-in-adaptive-optics/the-need-for-adaptive-optics-in-the-human-eye. Accessed on 2015/11/04.

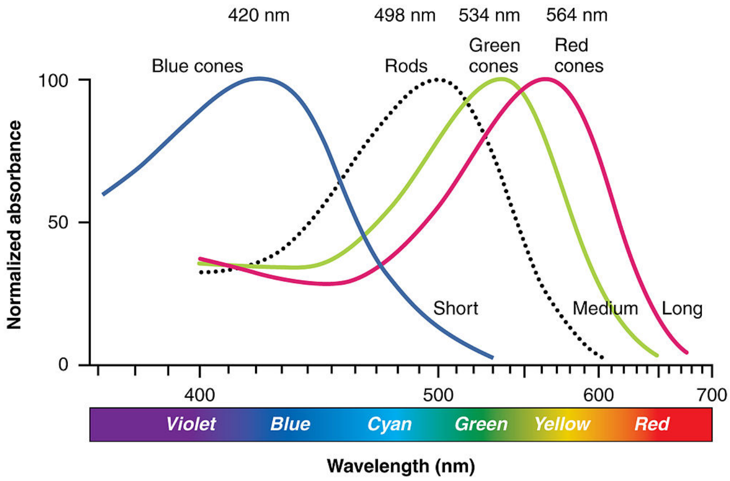

Figure 2.6: Diagram of Eye Color Sensitivity, depicting distribution between cones and rods.[7]

- S-Cones (Small Wavelength Sensitive), correspond to Blue color perception.
- M-Cones (Medium Wavelength Sensitive), correspond to Green color perception.
- L-Cones (Large Wavelength Sensitive), correspond to Green-Red color perception.

The difference between the signals edited from the three types of cones allows the brain to perceive a continuous range of colors. The distribution of the number of different cones can differ widely.

Rods

These photoreceptor cells function in less intense light, when compared to cone cells. They also acquire their name because of their elongated, cylindrical shape (the white colored shapes in figure 2.5); their location is on the outer edges of the retina, and the number of rods is around 78 to 107 million. These cells are much more sensitive than cones and they are responsible for night vision: in the dark, as your rods have only one type of light -sensitive chemicals, your ability to see gradually increases. This limitation in the types of rods is the reason why they cannot discriminate colors, as the cones. On figure 2.6, it is possible to compare the light absorbance for different wavelenghts, distributed among Cones and Rods.

All of this color information is, then, sent to the brain where it will be processed and associated to a mental model. Psychologists tried to explain how the complete color vision works, and formulated some theories about that.

2.2.3 Theories of Color Vision

The english physician Thomas Young published a theory [You02], where he stated that in the human eye existed three types of photoreceptors, the cone cells. Later in that century, he was joined by Hermann von Helmholtz when he concluded there exists three types of cone receptors and they could be classified as short-preferring, middle-preferring and long-preferring, according to their response to light's wavelength. Together, they formed the Young-Helmholtz Theory, or

[7] From: https://en.wikipedia.org/wiki/Photoreceptor_cell. Accessed on 2015/11/04.

the so called **Trichromatic Theory**. No single cone can detect by itself the color of a light: it is the ratio of the three types of cones that determine what color will be sensed by the brain. This theory was largely applied in the creation of color screens, for example televisions which contain microscopic elements of Red, Green and Blue.

Per contra, german physiologist Ewald Hering developed in 1878 a counter-theory: the **Opponent Process Theory**. This theory suggest that our color perception is controlled by three opponent pairs: red and green, blue and yellow, white and black[8]. Hering postulated that the members of each pair either oppose or inhibit each other, only one element can be signaled at one time, but not both at the same time: when one member of an opponent pair is no longer stimulated, the opponent pair is activated. For example, if you stare for a long period of time to a red subject, when you look away the afterimage will be red.

Together, these theories summarize what we know about color vision. We perceive color because of the three photoreceptors in our retina and sense different colors when exists different ratios in the three cone cells. The Trichromatic Theory explains how we see what we see in color, but it is only valid for the presence of all types of cells. What if some of them are absent?

2.2.4 Visual Deficiency

A color vision deficiency is the inability to distinguish a set of colors or, in some cases, total inability to distinguish any color at all. As said before, cones normally contain photospins which respond to particular wavelengths of light: people who have cones containing only two types of photospins, instead of three, are considered to have a **Color Vision Deficiency** (or colorblind, the most common term) and are able to discriminate fewer colors than regular people. Most people with color vision deficiency can see colors, but they find particularly difficult to differentiate between red and green, and blues and yellows, being the last one the least common deficiency.

Color deficiency is usually an inherited condition but injuries or chemical exposure can lead to color recognition loss: some of these factors include diabetes, leukemia, Parkinson's disease or Alzheimer's disease, or simply aging. These deficiencies can be classified as follows:

- **Monochromacy:** Known as "total color blindness" and is caused by cone defect or total absence of it. It occurs when two or all three types of cones don't exist and color and lightness detection is reduced from three dimensions, to only one. This condition is reasonably rare.
- **Dichromacy:** In this defect, one of the possible three cone chemical protein is missing. Is is an hereditary condition and it occurs when when one of the cone pigments doesn't exist. Dichromacy can be divided into three conditions:
  - Protanopia (from the Greek *prot-*), refers to the absence of red retinal photoreceptors. Protans find it hard to distinguish between red and green colors and blue and green colors.
  - Deuteranopia (from the Greek *deuter-*), where the green photoreceptors don't exist.
  - Tritanopia (from the Greek *trit-*), where the blue photoreceptors are absent. This type of dichromacy is very rare.

[8]"How to See Impossible Colors, Imaginary Colors and Other Stuff about Sight". Available at: http://somebloodyweirdo.blogspot.pt/2013/04/brain-hack-to-maybe-see-impossible.html. Accessed on 2015/11/04.

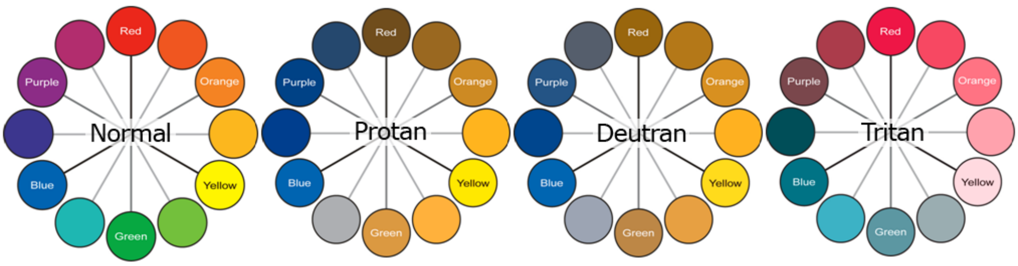

Figure 2.7: Correspondence of Colors Between Normal Vision, Protanopia, Deuteranopia and Tritanopia.[9]

- **Trichromacy:** In this defect, one of the three cone pigments is altered in its spectral sensitivity. Also, it can be divided into three conditions:
  - Protanomaly, which happens when the spectral sensitivity of red receptors is altered, and it is harder to distinguish red hues from green. The difference to protanopia is that, in this case, the L-Cones are present but they are deficient.
  - Deuteranomaly, causes a similar shift in the green receptors, also affecting the red-green perception. The difference to deuteranopia is that, in this case, the M-Cones are present but they are deficient. It is the most common color vision deficiency in the world, affecting 5% of European Males
  - Tritanomaly, which affects the blue-green and yellow-red/pink perception. The difference to tritanopia is that, in this case, the S-Cones are present but they are deficient.

Figure 2.7 maps colors seen between a person with a normal visual condition, a protan, a deutran and tritan.

Color deficiency can be diagnosed through an eye examination. During that test, it will be used specially designed figures composed with colored dots, called **Pseudisochromatic Plates**, which include a number or a figure supposed to be easily decoded by someone without a visual deficiency, as the example of the figure 2.8. The subject is asked to look at the plate with the figure and distinguish the number/figure: if it is easily unscrambled, the subject does not have a particular type of deficiency, if the number is not easily seen (or a wrong number is spotted), that constitutes an evidence of possible color blindness; further testing is required. This test was created by Dr. Shinobu Ishihara in 1917: the original test consisted of 38 plates, but later [Ish72], the author published a simplified version with 24 plates. This test has been used since then in many researches as an important first-step test.

Figure 2.8: Pseudisochromatic Plate, with number 74.[10]

2.2.5 Mental Models and Codes

Whether agreeing or not on its as an intrinsic existing characteristic, we perceive color on every subject we look at: if you look around, you will find no such thing you could not extract color as a description. In fact, one of the things you are taught by your relatives and educators is the

[9] From: http://www.stonesc.com/wordpress/2010/05/what-about-color-blindness/. Accessed on 2015/11/04.

[10] From: http://www.colour-blindness.com/colour-blindness-tests/ishihara-colour-test-plates/. Accessed on 2015/11/04.

concept of painting with color pencils, water colors, gouaches, oil ink or felt pens; mixing colors is a constant, you naturally learn how colors are disposed in a color wheel and, in most of the case, a subtractive color model like the **RYB** is taught (for purpose of understanding, a subtractive color model is one where the wavelengths of each paint is absorbed by the others, originating darker colors. This concept will be exhaustively explained later.) As Gosset *et al.* state [GC04], the usage or learning of subtractive color spaces, in childhood, modifies the mental color model of each person. Typically, these models are quite different from the **RGB** model, and this can create confusion to the observer, since these types of models constitute additive color spaces, leading to mixing-resulting different colors than the ones which constitute the mental model. Even if you think about that, different types of dyes or paint pigments have different mixing behaviors and generate different mixed colors. Gosset tried to create an alternative composition of colors in order to help naive observers, in the task of color mixing detection: he aimed to separate colors via noise patterns, to modulate the intensity of each color over a region; by consummating this, regions with multiple colors mixed would have sub-regions where one color contributes more than the others, and thus the user could figure out which colors (and in which percentage) originated that mixing.

Mental models help spreading color standards through the population and colors turn out to be instantaneously recognized as information. For example, in 1968 Vienna Convention on Road Signs and Signals [Nat95], it was standardized signing system for road traffic, from road signs and marks, to traffic lights; this convention was created to increase road safety, by creating consistent common rules every country should follow. This type of information encoding can vary from International Maritime Sinal Flags [AM03] (used on ships to transmit messages), to electrical wiring conventions, video-games, Military symbols, ranks in martial arts (known as "belts"), among many others.

Color is even perceptually different among different countries, continents, environments and genders: as is know by now [11], women can detect and describe with much more detail color than men, the photoreceptors of men take a little longer wavelengths to perceive hue of a color; this question remain to be fully researched, but it is the difference between genders is a certainty. In 2011, BBC shot a documentary[12] in which they explore the differences from the western color perception, and tribal color perception; the researchers presented a circle of squares with different shades of green (Figure 2.9), to the Himba tribe from Northern Namibia. Surprisingly, they were able to detect a larger number of shades than a western, non-colorblind person: this may occur because their environment do not manifest as much colors, and they need to detect different shades to hunt and pick up vegetation and fruits, which traditional western communities do not need to do.

Figure 2.9: Example of a Green Color Test made.[12]

Every color is mapped into models which mathematically represent them, despite of physical attributes of display conditions. All of these models are mapped against a Color Space that maps

[11] "Where Man See White, Women see Ecru", Available at: http://www.smithsonianmag.com/science-nature/where-men-see-white-women-see-ecru-22540446/?no-ist. Accessed on: 2015/10/30

[12] "It's Not Easy Seeing Green", Available at: http://6thfloor.blogs.nytimes.com/2012/09/04/its-not-easy-seeing-green/, Accessed on 2015/10/30.

the real-world colors in discrete values: perhaps, one of the most interesting and relevant creations on the field of Color Perception Research is the **CIE 1931 Color Space**.

2.3 Color Models and Spaces

2.3.1 Colorimetry

Mixing the three primary color light channels to match any color is no longer an oddity and it constitutes the basics of colorimetry: it is the science used to quantify and describe the human perception of color. We can describe color as the following equation [War12]:

$$C = sS + mM + lL \tag{2.1}$$

where C stands for the color to be matched, S, M and L are the primary light sources used to create the final color and that are detected in three types of cones, s, m and l represent the precise amounts of each primary lights. Not only by adjusting these primaries, but also by modifying their values, it becomes possible to state any colored light, describing it as a weighted sum of any three distinct primaries; this is the fundamental principle of colorimetry, the freedom to change from one set of primaries to another, grounding the decision on phosphors of a monitor, a set of lamps or on the sensitivities of the human cone receptors. Of course, this freedom comes with a price: it would be very difficult do maintain and calibrate standardized lamps, specials instruments to evaluate color precision would be very expensive and this would not be very practical. To solve this, it was assumed that every human being had about the same sensitivities to different colors (excluding the obvious color deficiencies), and the same receptor functions; it was the time to start creating color specification standards and understand the principal concepts of it.

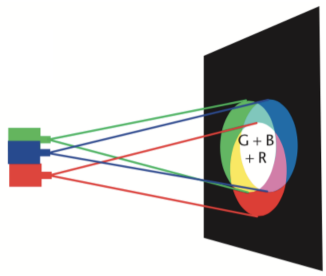

Figure 2.10: A Color-matching setup. [War12]

2.3.2 Color Fundamental Concepts

The organization and perceptual evaluation of color depends on some concepts which have been briefly referred before. They will be explained in this report helping us to understand how every color model and spaces work. This concepts are listed below, with an appropriate explanation seeking them.

Hue As defined in **CIE Color Appearance Model of 2002** [MFH$^+$02], hue is "the degree to which a stimulus can be described as similar or different from stimuli that are described" as red, green, blue, yellow, orange or violet. In case of two colors that are presented with the same hue, the distinction is made using adjectives referring to their lightness or colorfulness. Also, it was created the term "Unique Hue" to describe those colors that are instantaneously recognized as pure, the ones which do not are the resulting product of a mixture; the color perceptions as unique are only four: Red, Green, Blue and Yellow. The concept of Hue is represented in Figure 2.11, on the left column.

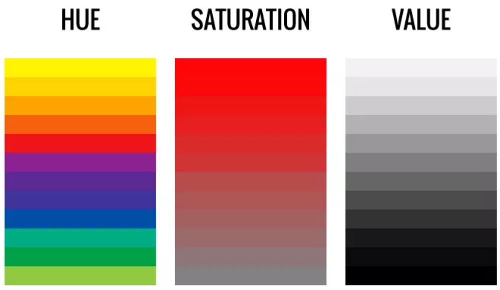

Figure 2.11: Comparison between Hue, the concept of Saturation and Lightness (or Value).[13]

Saturation This is a color term commonly used by imaging experts, to define a range from **pure color (100%) to gray (0%)**; a pure color is fully saturated. From a perceptional point of view, saturation influences the grade of vividness or purity of a subject: a desaturated image is said to be dull or washed out, creating the impression of being softer. In other words, saturation is determined by the combination between light intensity and its distribution across the spectrum; the purest color is obtained with high-intensity wavelength and, as this wavelength drops, the saturation also drops and the color "walks" straight into the gray. For example, in Figure 2.11, it can be seen different saturation values for Red Color, varying from the purest red to gray. However, this concept must not be confused with **Colorfulness** (which is the absolute color intensity of a light stimulus) and with **Chroma** (which refers to the perceived strength of a surface color).

Lightness This concept is usually known as **Value or Tone**, and is related to the variation of light in the subject, either lighter or darker (as seen on the right column of Figure 2.11): light colors are called **Tints** and dark colors are called **Shades**. It defines the range from **dark (0%) to fully illuminated (100%)** and judges the brightness of an illuminated area, compared to another area that appears to be white or highly transmitting.

Brightness It is an attribute of our perception, highly influenced by color's lightness, but not to be confused with it! It is the perception of whether a subject is radiating or reflecting light. For one color of a given hue, the perception of brightness is influenced by its saturation: if we increase it, the color also looks brighter.

Luminance It is a measurement of light, which assess the luminous intensity of a color. You can lighten or darken a color by adjusting its lightness value, but lightness is not the only dimension to consider for luminance: that is because each hue has an individual luminance value; if luminance is dependent on hue, it is also dependent on saturation; by reducing the saturation value of any pure hue to 0% results in a 50% gray and 50% value in luminance. For hues with natural luminance above 50%, the luminance decreases when saturation level decreases; contrary, if the luminance is below 50%, it will increase when the saturation level decreases. The Figure 2.12 describes the percentage of white that each hue contains, being white the maximum percentage of 100%.

[13]From: http://blog.plot.ly/post/125942000947/how-to-analyze-data-6-useful-ways-to-use-color-in. Accessed on 2015/11/04.

[14]From: http://www.workwithcolor.com/color-luminance-2233.htm. Accessed on 2015/11/04.

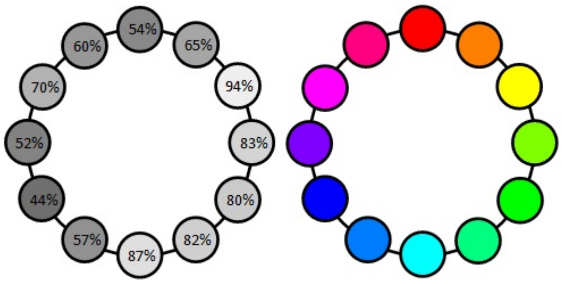

Figure 2.12: Luminance schematic.[14]

Chromaticity Similarly to what happens with saturation, it is an objective specification of the quality of a color, but regardless of its luminance. As it will be seen in a while, it is what is shown in the CIE 1931 XYZ Color Space Diagram.

Contrast This concept estimates the influence of luminance that makes an object distinguishable from a background. The Human Visual System determines contrast by the difference in the color and brightness of the object and other subjects within the same field of view.

Temperature This is a characteristic of visible light with important applications in lighting, photography and other areas. It is the temperature of an ideal black-body radiator (one which absorbs all electromagnetic radiation that reaches it) which would radiate light of similar hue to the radiating light source. Cool colors are the ones with temperature over 5000 Kelvin (K), conveying a bluish white color; warm colors have temperature around 2700 K to 3000 K. For example, the light emitted by a candle flame has a temperature of 1850 K and an orangish color, opposite to the color temperature of a clear blue sky, which temperature goes around 15200 to 27000 K.

Being the most relevant concept of color introduced, it is time we start establishing relationships between them: this type of relationships are created and reflected in color spaces and models, typically with three or four color components. There is a fairly generous amount of them, but only a portion of these are interesting to our research.

2.3.3 Color Spaces and Models

The concept of Color Spaces and Models is often confused but, in fact, they do not present the same idea (although they do use similar conceptions). Then, color models appear to mathematically conceive a description of color, in which color spaces will be based. It is relevant to settle a distinction among them, paying special attention to the fundamental CIE Color Space, which is acquired as one of the most fundamental perception studies.

Color Models

A color model is a mathematical description of color. The difference to a color space is that the latter represents the range of colors described by a color model, being able to describe the entire range of perceivable colors by the human visual system, something a color model does not detail. This color systems dependent on the media the subject is represented: if it is represented as a painting, colors have different behaviors than if they were mixed using light sources.

There are two types of color models: additive and subtractive. **Additive Color Models** use light to display color mixing, mixing primary colors such as Red, Green and Blue; equally combined and overlapped, they form white light, whereas **Subtractive Color Models** mix colors using paint pigments and the result of any mix is a color that tend to be darker, the more you mix it. Additive models are used in computer graphic displays, while subtractive models are commonly associated to dyes and inks. Examples of this color models are given below [War12].

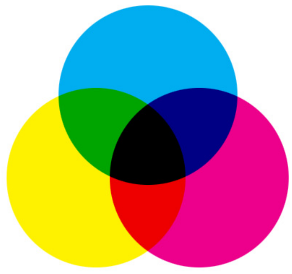

Figure 2.13: RYB Color Model.[15]

RYB One of the first models to appear was the RYB color model, an abbreviation for Red-Yellow-Blue, created in the late 16th century by Franciscus Aguilonius in the belief of having a set of colors capable of creating all other colors, when mixed. This theory was considered a standard almost for two entire centuries: even Newton used it on his famous work "Optiks" (1706) about light refraction and diffraction, creating a color wheel which represents the relations among colors. In the beginning of the 18th century, the RYB model served as the base to fundamental studies about color vision: the german poet Joan Wolfgang von Goethe, published a relevant work about his visions on the nature of colors and how they are perceived by humans under different circumstances; his work was widely accepted between philosophers, since its analysis was more focused on the human perception of color and not so much on the analytic specification of color.

This color model is a **subtractive color mixing model**, in which the primary colors are Red, Yellow and Blue, and the secondary colors are Orange, Purple and Green. However, this model was quite limited in what was concerned about color perception, it was necessary to specify a new model which would create a standard in representation of images on display devices.

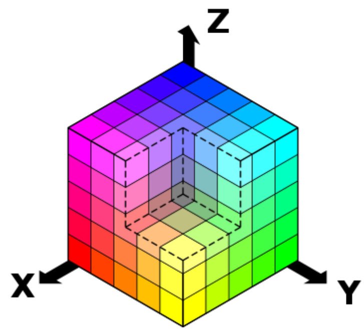

Figure 2.14: RGB Color Model.[16]

RGB Subsequently, the RGB color model stood out as an additive model in which Red-Green-Blue colors were mixed together to produce a wide field of colors; the RGB model is closer to the way human vision encodes images. When combined, red and green light rays produce yellow, red and blue produce magenta (or purple) and blue and green produce cyan. For example, this color model is used in Cathode Ray Tube monitors, flat-panel displays, video projectors and light systems in theater; this characterizes this model as a device-dependent color model. When all three primary color channels are 0 percent, the result is black color. If all three primaries are 100 percent of its intensity, the result is white. This color model is represented as three dimensional cube, with each corner being the purest colors, as in the Figure 2.14. There are several subsequent RGB color spaces, such as the **sRGB** (the most commonly used RGB space, in media devices), the **Adobe RGB and Apple RGB** which define their own particular gamut of colors.

[15] From: http://www.fountainpennetwork.com/forum/topic/291844-ink-mixing-primary-secondary-tertiary-colours-and-beyond/. Accessed on 2015/11/04.

Nonetheless, this color space needed improvements, specially a better geometrical representation which does not create an accurate match to the color mixture recognized by human vision.

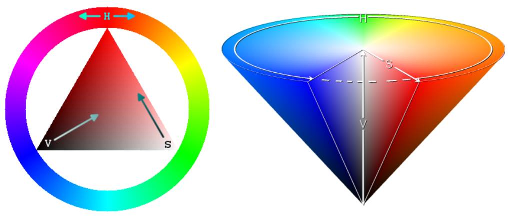

Figure 2.15: HSV Representations.[17]

HSV and HSL The HSV model was developed to correct the flaw in RGB. This acronym stands for Hue-Saturation-Value, depicting a three-dimensional color model: it aims to present relationships between colors, which is a direct improvement from RGB. There are several geometrical representations of this model, from cones to cylinders, but all of them provide the same visualization and concept disposal: Red, Green, Blue, Magenta, Yellow and Cyan **hues** are equally disposed in a circumference of a circle composing the color wheel, (you can think of it as a cut of the cylinder, or the cone base) with the white color in the center; from the center of the circle towards the outer edge, varies the **saturation** of colors, being the most saturated the farthest position from the center. In a perpendicular edge departing from the center of the circle until the bottom of the cylinder/cone, it oscillates the value, being the bottom value equal to 0 and the darkest color (black), the lightest color (white) on top and, in-between, colors vary its darkness. The perception of relevant color proximity that this model brings is counter-posed by the lack of perceptual uniformity.

It was proposed a parallel model to HSV, which was called **HSL** due to its resemblance to the first. The main difference of this model lays on the last color component used, which is Lightness. Here, the value's axis is substituted by lightness, which in this case makes the bottom completely black and the highest plane completely white; a very common representation of HSL is the bicone or a cylinder. Both HSV and HSL are examples of **additive color models**.

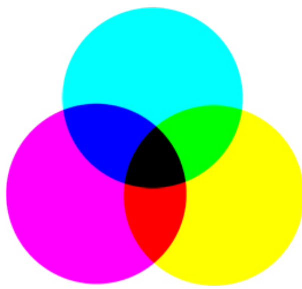

Figure 2.16: CMY(K) Color Model Representation.[18]

CMY(K) ~~The~~ CMY(K) works as a subtractive color model, with four color components, and is primarily used in printing industries, given the feature of printed ink of reducing the light that otherwise would be reflected. It is composed by four color: Cyan-Magenta-Yellow-Key. Key value is representing the black color, which is used because the combination of the three primaries does not produce a fully saturated black color. This color model is able to produce the entire color spectrum of visible colors, due to the **half-toning** process it executes: tiny dots of each primary color, with an assigned saturation, are printed in a pattern small enough so it is perceived as a solid color. This process allows the printing of more than seven colors, the amount of possible mixture combinations which could be created if the primary colors were printed as a solid block of color. In order to improve the print quality and reduce moiré patterns, the screen for each color is set at a different angle. This configuration is shown in 2.17.

This color model may be viewed as the inverse of RGB color space, since it represent all the colors produce by the mixture of RGB colors: Green-Blue produce Cyan, Red-Blue produce

[16]From: https://commons.wikimedia.org/wiki/File:RGBCube_b.svg. Accessed on 2015/11/04.
[17]From: http://www.ccs.neu.edu/course/cs4300old/s10/L5/L5.html. Accessed on 2015/11/04.

Figure 2.17: Half-toning patterns presented on the left image and different angles at the right image.[19]

Magenta and Red-Green produce Yellow. CMY(K) is a device-dependent space, since it depends on the printer used to imprint the subject.

Color Spaces

A color space is a mapping of a given color model to a particular organization of colors, which allows the representation of reproducible colors on a given physical device. It relates the mathematical description of a color model to actual colors, being a three dimensional object that contains all realizable color combinations. They can be, generally, grouped onto three categories:

1. **Device-Dependent Spaces**, which express color relative to some other reference space. It indicates the subset of colors which can be displayed using a particular device (*e.g.* a monitor or a printer) or captured by a recording device.

2. **Device-Independent Spaces**, which express color in absolute terms, serving as universal reference colors.

3. **Working Spaces**, used by image editing software and file formats to constrain the range of colors to a standardized palette. For example, one of the most used color working space is Adobe RGB 1998.

There were two relevant studies made about color spaces: the fist one is the **Munsell Color System**, which had began in 1898 and saw its full expression in 1905; the second is one of the principal color spaces used to describe the entire range of human perceivable colors, which is the **CIE Color System**. The CIE space of visible color is expressed according to different components: **CIE 1931 XYZ, CIE-L*a*b* and CIE-L*u*v***, and all three present the same range of colors.

Munsell Color System One interesting color system is the one created by Professor Albert H. Munsell in the first decade of the 20th century [Mun19]. This was the first system to separate hue, value and chroma into perceptually different dimensions, and also illustrate in a systematic way these components in a three dimensional space. It consists of a cylindrical color solid, where value is measured vertically from 0 (black) to 10 (white), hue is measured in degrees around horizontal circles and chroma, radially measured in concentric circles.

[18] From: http://www.ashworthcreative.com/blog/2014/06/difference-cmyk-rgb-colors/. Accessed on 2015/11/04.

[19] From: https://en.wikipedia.org/wiki/Halftone. Accessed on 2015/11/04.

Each circle of the cylinder is divided into five principal hues: Red, Yellow, Green, Blue and Purple, where intermediate hues can be found in-between the principal ones. Two colors with equal chroma and value - residing in the same circle - but found on opposite sides are complementary colors, and create gray color found in center of the circle, when mixed together. Colors in this system are defined in the format **"H V/C"**, for example, "5R 5/10" means Red Hue, with 5 meaning middle value and a chroma of 10, indicating a high level of purity. In 2.18, it is represented the circle of hues at value 5 and chroma 6, most precisely chromas for Purple-Blue. This color system is still in usage nowadays, being the basis for numerous models such as **CIE-L*a*b***.

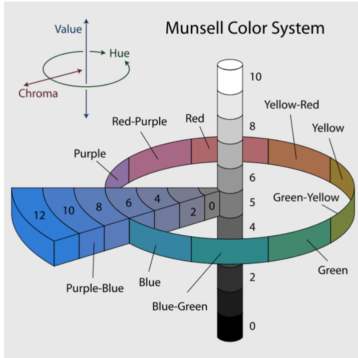

Figure 2.18: Munsell Color System.[20]

<u>**CIE 1931**</u> The *Commission Internationale de l'Éclairage* (**CIE**, or International Commission on Illumination) defined in 1931 the first set of color spaces, which defined the mapping between physical pure colors and standard observer measurements of perceived color: they are, nowadays, identified as the **CIE 1931 Color Spaces**, and can be disjointed onto two spaces: the **CIE 1931 RGB Color Space** and the **CIE 1931 XYZ Color Space**. Remembering section 2.2.2, we discussed the existence of three types of cones, S, M and L, which correspond to three different types of cone stimulation; the CIE color space maps the range of physically produced colors to a description of color sensations registered by the observer, which come in terms of *tristimulus values*: this system uses a set of abstract primaries abstracted to XYZ, chosen for their mathematical properties (instead of SML *stimuli*) which will cast the color perception into this new coordinate system. The **CIE XYZ** comprises all color sensations a human can perceive, standing out as a standard for other color spaces and the tristimulus values have the following properties:

- All tristimulus are positive for all color. The XYZ axes are purely abstract, but all perceived colors fall within CIE gamut *i.e.* complete subset of colors.

- The X and Z values have zero luminance, being the Y value the only one which represents luminance information. By defining this, the CIE space allows the XZ plane to contain all possible chromaticities (a specification of a color, regardless of the luminance) at a given Y luminance.

The CIE 1931 color diagram, as seen on the Figure 2.19, represents all the chromaticities visible to an average person, called the gamut of human vision. It has a horseshoe shape, due to its curved edge that represents the edge of human perceivable colors, also known as the spectrum locus; on the bottom of the graph, a straight edge can be seen and it goes by the name of line of purples (or Purple Boundary), going from red to violet. All of this edges are considered to be the only fully saturated colors. The **chromaticity diagram** has some interesting properties [War12]:

- If two colored lights are represented by two points in the diagram, the resultant color of those two points' mixture will always lie on a straight line between them.

[20] From: https://en.wikipedia.org/wiki/Munsell_color_system. Accessed on 2015/11/04.

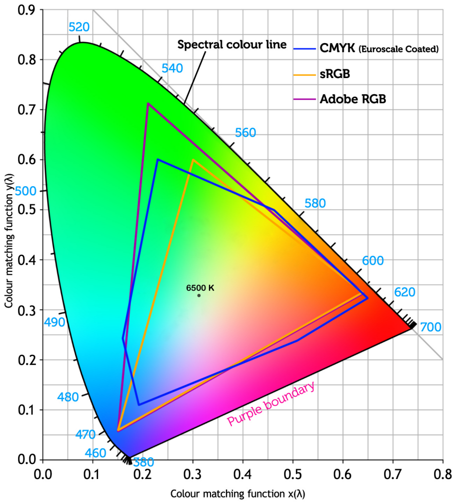

Figure 2.19: CIE Color Diagram, with CMY(K), sRGB and AdobeRGB Color Gamuts depicted.[21]

- Any set of 3 light specifies a triangle in the diagram: each corner represents a different light source. Any color within this triangle can be created by a mixture of three lights.
- CIE defines a standard for white light illumination: it specifies a number corresponding to different kinds of daylight. The most commonly used is **D65**, chromaticity coordinates being:

$$x = 0.313, y = 0.329 \tag{2.2}$$

  To contrast, **Illuminant A** (an incandescent tungsten light source) has coordinates:

$$x = 0.448, y = 0.407 \tag{2.3}$$

  which is considerably more yellow than normal daylight.
- The vividness of a color is defined by the excitation purity, which quantifies distance along a line between a particular pure spectral wavelength and the white point of the diagram.

The CIE Color System is both a Color Model and a Color Space since, at the same time, it describes a mathematical representation using XYZ primaries and represents the superset of the entire range of human perceivable colors. The **CIE RGB Color Space** is one of the many subsets of CIE XYZ; in Figure 2.19, it is identified in the CIE horseshoe different color models, such as the sRGB, AdobeRGB and CMY(K).

CIE-L*a*b* It is a device-independent color space based on color-opponent axis, created in 1976. The two axis are represented by the **a* and b***, where the first one represents the Red-Green axis and the latter the Blue-Yellow one; the **L*** variable represents the lightness. This color space is often used when graphics have to be printed and converted from RGB to CMY(K) color model, as L*a*b* space contains both color gamuts. The asterisk that follows each variable is meant to be read as "star". There are some particularities related to this space, which can be seen on Figure 2.20:

- The values for the three variables are absolute, with a pre-defined range.

[21] From: http://www.saxoprint.co.uk/blog/cmyk-colour-model-colour-space/. Accessed on 2015/11/04.

- $L^* = 0$ represents black and $L^* = 100$ the brightest white.
- As for the a* and b*, they will represent a neutral gray value at 0 value.
- On the Red-Green Axis, represented by a*, the positive end a* being the Red component and the negative end the Green component.
- On the Blue-Yellow Axis, represented by b*, the positive end b* being the Yellow component and the negative end the Blue component.
- The value limits are implementation-dependent, since they can vary between -100 and +100 or -128 and +127.

This color space derived into a cubic color space representation, which is recognized as the **CIE-L*C*h***, where the Cartesian coordinates of a* and b* are substituted cylindrical coordinates **C* and h***: the first one stands for **Chroma** and the second one for the angle of the **Hue** in CIE-L*a*b* color wheel.

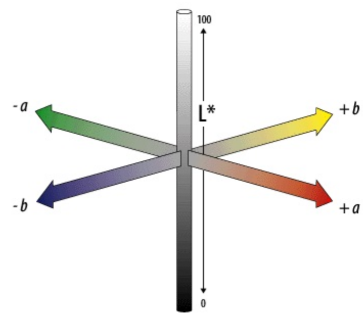

Figure 2.20: CIE-L*a*b* axis.[22]

CIE-L*u*v* This space was created to correct the CIE XYZ space which was inadequate because the two-dimensional diagram failed to give a uniformly-spaced visual representation of a three-dimensional color space. This was achieved by distributing color proportional to their perceived color difference. It is largely used nowadays by computer graphics systems which manipulate colored lights. In this space, the **L*** has the same significance as the CIE L*a*b* space; **u* and v*** redefine x and y to present a visually more accurate two-dimensional model. Just like CIE XYZ and CIEL*a*b*, this color space is also device-independent and therefore is not restrained by color gamut. These color spaces and models describe how we can relate color with each other, besides explaining how we can use them in man-made display devices. This raises a problem, since man-made devices present different configurations and can use different color spaces or models, which are manifested in the size of color gamut that can be presented. The solution is to calibrate color in those devices.

2.3.4 Color Calibration

The accuracy of color is critical in design: the color you see on a monitor is never what will appear on a printed sheet. The aim of calibrating a color is to adjust the color response of a device, establishing a relationship to a standard color space or model. This represents an important step when performing a color perception research, since perception of a color is influenced by the light sources incident in the device, the color space used by the device and the existent calibrated color of it. There are numerous ways to perform a calibration of color, either by software or hardware: for example, there are physical devices which can be placed close to the device screen and will stimulate individually every pixel according to a concrete color setup, defined by the user.

[22] From: http://dba.med.sc.edu/price/irf/Adobe_tg/models/cielab.html. Accessed on 2015/11/04.

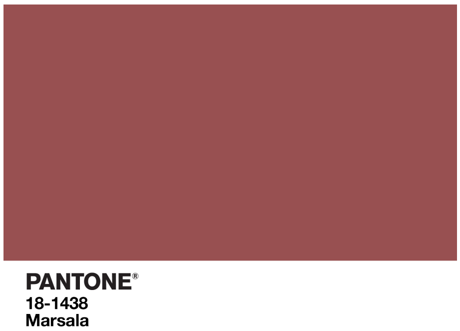

Figure 2.21: Pantone 18-1438 Marsala.[23]

Nonetheless, calibration standards were created to ensure the color correctness and expectation. The **Pantone Matching System (PMS)** is a commercial standardized color reproduction system; by creating this standard, printers and manufacturers around the world can refer to a specific Pantone color code to make sure colors match with no doubt. The PMS is recognized also, by the printing of a small catalogue with a large number of small sheets which contain every possible Pantone color, in every tint or shade. The type of paper used will affect the appearance of colors: Pantone covers this problem by showing how desired color will look on coated, uncoated or matte paper[23]. PMS is used in a variety of industries, primarily offset printing.

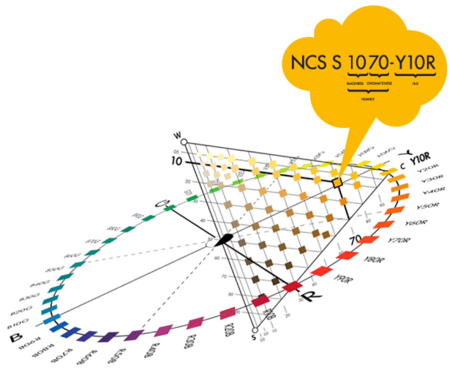

Figure 2.22: NCS S 1070-Y10R.[24]

Another commonly used standard is the **Natural Color System (NCS)**, based on the color opponent axis description: there exist three pairs of opponent colors, the White-Black, Green-Red and Yellow-Blue, which were introduced by Ewald Hering [War12]. The NCS is based in mechanisms involved in signal processing in the ganglion cells in retina, which orientates the light to retinal cones before it is sent to the brain; this is different from what happens with RGB, where information is acquired at low level on the cones and rods. This color system is based on the six elementary colors referred in the beginning of the paragraph; colors in NCS are defined by three values, specifying the amount of **darkness, the chromaticity and a percentage value between two of the colors**. The intuit of this color system is create color codes that can be spread and understood across the world. To define a color in this color system you need to[24]:

1. Identify the closest matching color area in the NCS Color Circle, which will give the family name of that color, the hue.

2. Find you shade or tint in the color triangle of the color chosen in the first step. This will give you its darkness and chromaticity, which must add up to 100%: if a percentage value remains, it is attributed to whiteness.

3. Write the full name, preceding with "NCS", adding "S" if the color is an NCS standard color.

For example, **NCS S 1070-Y10R** translates into a NCS standard color perceive as: 90% Yellow and 10% Red, with 10% of Whiteness and 70% of Chromaticity value. Since 10% + 70% = 80%, the remaining 20% belongs to Whiteness. This color is shown in Figure 2.22.

[23]"The Pantone Matching System®", Available at: https://www.pantone.com/the-pantone-matching-system. Accessed on: 2015/10/30.

[24]"How To Comunicate Your Color.", Available at: http://www.ncscolour.com/en/natural-colour-system/logic-behind-the-system/. Accessed on: 2015/10/30.

2.3.5 Color Usage

We have grounded how color is represented *via* color models and spaces, and what are the main concepts related to color understanding. However, color is used in different scopes and can be presented by itself or accompanied by other colors. Foremost, we have to analyze light to understand what originates color and how we can create schemes to relate colors: visible light is electromagnetic radiation in the range of sensitive wavelengths to human eye, about 400 to 700 nanometers [JG78]. Therefore, perceived color is a spectral distribution of amplitude by wavelength, where the shape of distribution determines what is the color perceived. If this light has a flat distribution or any other distribution that stimulates all three cones equally, it will produce an **achromatic color**: either black, white or gray. Any other type of distribution produces a **chromatic color**.

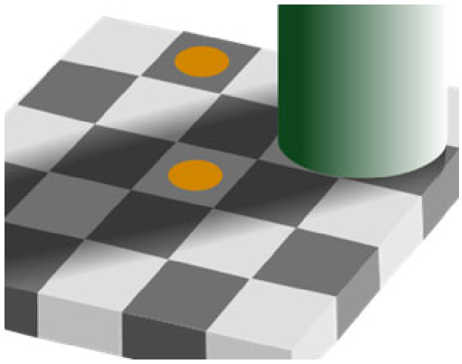

Figure 2.23: The Adelson Illusion.[25]

The color of an object, as we have discussed before on section 2.2.1, is both environmental and perception-dependent. Physically, the perceived color is related to the color of light that leaves the surface of the object, which depends of the color spectrum of the light source and reflectance properties of the material, besides the angle formed between the light source and the surface of reflectance, or even the angle of view. Materials have different behaviors, they can transmit, reflect or emit light, being the latter a contributor to the perceived color also: if the electrons are excited due to high temperatures is created a **incandescence** phenomenon, or **phosphorescence** if the light is absorbed at a shorter wavelength than the light that is emitted. Apart from these behaviors, perception is modified by the surroundings of the color: the Adelson Illusion (Figure 2.23) is a perfect example to prove that the human perception system is gifted with the feature of Color Constancy, that let us perceive that a color is still the same color, regardless of the background, lighter or darker. For example, an apple is an apple in the morning when the sun rises, it is the same apple in the sunset and it is the same apple at night, we perceive the object as equal independently of the lighting conditions; this helps us to recognize objects. In the illusion of Figure 2.23, the orange circle in the shadow appears brighter than the other circle but they are, in fact, exactly the same shade of orange.

Since the start of the research on this area in the 16th century when Franciscus Aguilonius created the RYB model, color representation was an important step in the creation of a mental model of color.

Color Organization

Sir Isaac Newton developed the first circular diagram of color in 1666, when he started experimenting the phenomenon of color, which people thought until there color was a mixture of light and darkness; Newton decomposed color with a prism, projecting the light spectrum on a wall. To prove the prism was not coloring the light, he refracted light back together with another prism.

One of his most useful ideas was the conceptual arrangement of colors around the circumference

[25] From: http://www.brainhq.com/brain-resources/brain-teasers/adelsons-same-color-illusion. Accessed on 2015/11/04.

Figure 2.24: Color Wheels representing Primary, Secondary and Tertiary Colors.[26]

of a circle, arranging primary colors opposite to their complementary colors, which became very useful for painters; later, the concept of secondary and tertiary colors was introduced and derived from the equivalent number of primary and/or secondary colors. **Primary Colors** were considered to be Red,Yellow and Blue, **Secondary Colors** were Green, Orange and Purple, which are formed by mixing only primary colors; on his turn, **Tertiary Colors** were created by mixing primary colors with adjacent secondary colors, deriving into Yellow-Orange, Yellow-Green, Blue-Green, Blue-Purple, Red-Purple, Red-Orange. However, it was only in the year of 1810 that Johann Goethe [Goe10] introduced the first systematic study of the human perception of colors, providing a symmetric arrangement of the color circle, regularly referred to as **Color Wheel**.

In order to correctly use color, an harmony must be created to pleasantly convey information: it engages the viewer and creates a sense of order and balance in a visual experience. The opposite of this is chaos, with the user neglecting the subject, since the brain neglects what is not organized because it cannot extract information and organize it. This color combination, however, has to be handled with care: unity and over-conformity will provoke under-stimulation, chaos and extreme complexity will cause over-stimulation.

This allows us to use harmony to create an equilibrium, which some theories already cover: the theories are called **Color Schemes**, that can be used over a numerous types of information channels, including the web. There are a few schemes already in use, which are covered below:

Monochromatic This color scheme uses only one hue and then adds black or white to create, correspondingly, various **shades** and **tints**. This is the most simple color scheme, since it is known that colors will work together if the base color and derived colors are similar. As seen in the Figure 2.25, a Purple color can be chosen, adding black or white to create tints and shades which look similar to the original color.

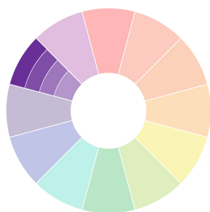

Figure 2.25: Monochromatic Color Scheme.[27]

[26] From: http://www.practicalecommerce.com/articles/3247-Understanding-Color-Theory. Accessed on 2015/11/04.

[27] From: http://webdesign.tutsplus.com/articles/understanding-the-qualities-and-characteristics-of-color--webdesign-13292. Accessed on 2015/11/04.

Analogous This scheme is created by choosing three adjacent hues in the color wheel; this color scheme can be used by admitting one hue as the key dominant color and the other two as supporting colors, used more sparsely to highlight the main hue. These colors usually match pretty well, creating a serene design; because of this, it can be both tedious or the ideal color scheme for a design that is primarily one color. On Figure 2.26, the top-left wheel shows Red as Key, and the adjacent colors as Supporting.

Complementary The complementary color scheme is created when two opposite colors on the color wheel are chosen, causing an vibrant look (or even aberrant, if not correctly managed) since they offer extremely high contrast. Complementary color schemes are tricky to use in large proportions, but work fairly well when you want a subject to pop out of the background. The top-center wheel on Figure 2.26 depicts Red and Green complementary color scheme.

Split Complementary Rather than choosing an opposite hue to the key color on the wheel, this color scheme takes two colors directly on the other side of the main color, both adjacent to the one which would be chosen to create a complementary color scheme. This scheme should be used as the analogous, choosing a key dominant color and the other two colors stand as supporting colors. On the Figure 2.26, the key color Red is supported by Blue and Green (top-right wheel).

Triadic This color scheme uses three colors that are equally separated around the color circle. This color scheme usually ends up being bright and vibrant: too much of each color and the design appears to have too many colors. This scheme should be used as the Analogous and the Split Complementary, choosing a key dominant color to be the focus and the other two colors stand as supporting colors. A possible combination is choosing Red as the key color and dark blue and dark green as supporting colors (bottom-left wheel on 2.26).

Tetradic This is very similar to Triadic Color Scheme, but instead of three colors, you choose four equally distant colors on the wheel. It is as creating a square around the color wheel. An example is Red as key, purple, yellow and green as supporting colors (bottom-right wheel on 2.26).

Color Scales

The expressive power of color is, by now, undoubted and because of that, color is commonly used in data visualization in order to convey various types of information. It is derived into color scales, which are pictorial representations of a set of numerical or categorical values, with every value having a matching color; by attributing different colors to different values, we can create a gradient of colors which eventually transmits continuity and the idea of perceptual steps. Penny Rheingans [Rhe00] surveyed some common (and not common) techniques for color scales used to present univariate and bivariate data.

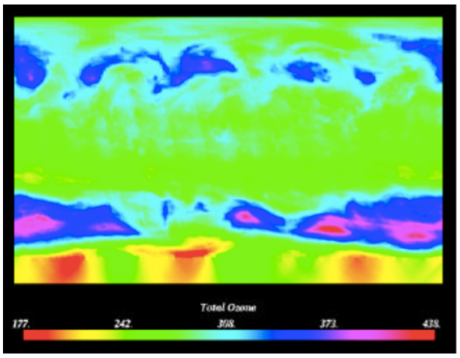

Figure 2.27: Spectrum Scale. [Rhe00]

[28]From: http://www.zevendesign.com/color-harmony-hulk-wears-purple-pants/. Accessed on 2015/11/04.

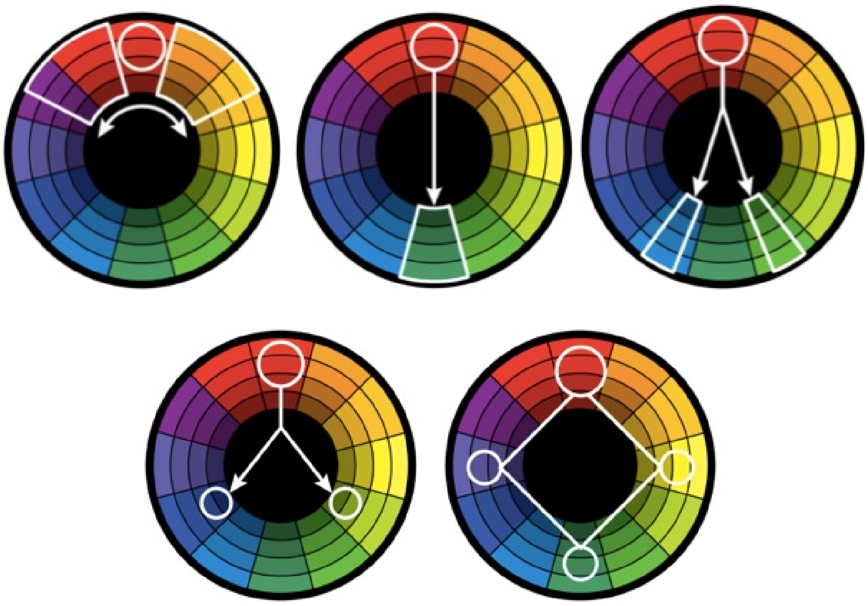

Figure 2.26: Color Wheels Representing on the first row Analogous, Complementary and Split Complementary. On the second row, Triadic and Tetradic Color Schemes.[28]

For Single-Variable Color Scales, a **Saturation Scale** can be created by keeping the hue invariable, oscillate the color saturation; the biggest advantage is the simplicity and its intuitiveness, the biggest disadvantage the low PDR (Perceived Dynamic Range). Also, **Spectrum Scale** (Figure 2.27) is a very commonly used scale, keeping the saturation and brightness invariables, oscillate hue within its full range (from red, orange and yellow, to yellow, green, blue and then purple). The problem lies in the fact that this scale is not intuitively continuously perceived for all observers[29]: perceptual discontinuities occur in the scale in the transitions between primary colors, in the "naming boundaries" of each color (the boundaries of primary colors that can be described and named by a user), which can mislead the observer and make him perceive limits where they don't exist. For a protanopic person, rainbow color scales appear to have repetitive colors. Also, there are colors that appear brighter than others, for example, yellow because it activates both M and L Cones (Green and Green-Red, respectively), creating the false expectation of a greater value associated to yellow.

Sometimes, as Levkowitz explained [Lev96], the **Gray Scale** is the most used, being black the lowest value and white the highest value: its advantage is the efficiency for the human visual system; however, it has a limited PDR and, combined with aesthetic reasons, people tend to seek alternative color scales. **Heated-object Scale** (Figure 2.28) is also very common, by combining gray scale and spectrum scale, it augments monotonically with luminance; it fluctuates from black, to red, orange to

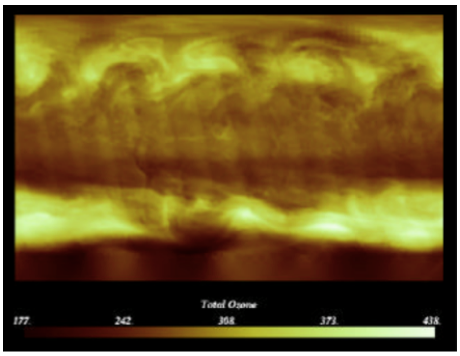

Figure 2.28: Heated-Object Scale. [Rhe00]

[29]"Dear NASA: No More Rainbow Color Scales, Please", Available at: http://blog.visual.ly/rainbow-color-scales/. Accessed on 2015/10/30.

yellow and, in the end, to white. It happens to have more distinguishable perceptual steps and more contrast, than the gray scale.

Rheingans defines **Hue-Other Scales** for two or more variables, as mapping variables to different color models, like hue, lightness ou saturation (this concepts will be defined later). Lightness gives the perception of order, as we perceive the values as having a natural order. It is also easier to judge the relative magnitude of two lightness values than of two hues. For example, areas with similar hue values, but differing lightness, are easier perceivable as related than areas with similar lightness, but different hue.

2.3.6 Color Blending

As it is perceived by now, color has multiple areas of study. Furthermore, color plays an important role on how we perceive subjects and in the information we extract from them. Color is usually associated to the representation of information, due to is expressiveness and the familiarity that users have: if you picture a graph or a chart, you instantaneously think of colors to represent variables.

Ideally, you represent more than one variable or concept in the same chart or visualization, each one with a different color; blending these colors could show information in a way that separate colors could not, but could also create confusion in user's perception. As Gossett stated [GC04], color blending only works if the users have the accurate perception of colors which originated the mixing.

The perceptual accuracy of users, regarding the perception of relative amount of colors and the visualization of social artifacts has already been studied: could we use, in an efficient way, color blending to demonstrate information?

2.4 Color Blending Investigation and Techniques

Visualizing information is a task which, at the same time, communicates information and alleviates cognitive load associated with data interpretation. Usually, when it comes to encoding information, color appears as the number one choice, due to the its ease of perception and familiarity. When representing more than one colored variable at the same time, it would be useful to perceive interrelations among them and if the users are able to understand which of these entities are related, or blended: this leads us to the idea of blending colors together to form a mixture, conveying more than one channel of information. Research has been made to conclude if people can distinguish different percentages of blended colors or associate colors to daily-basis tasks, *e.g.* reading and receiving emails.

On the other hand, researchers have been developing alternatives to color mixture, enabling the end users to create different perspectives on how color is related; as we are going to see, color blending has its features and flaws, which parallel techniques try to recover.

2.4.1 Color Blending Investigation

Until the year 2014, some aspects remained to be studied. Gama and Gonçalves started their research [GG14b] aiming to study to which extent people are able to, given a specific color resulting from a mixture of two colors, understand the blended color's origin; besides, they studied which is the color model that yields the most accurate results: hardware-oriented color models like RGB or color-printing models such as CMY(K), fail to provide a color perception description, unlike HSV. This pitfall is amended by CIE-L*C*h*, by creating a perceptually inform scale to lightness.

Data Visualization

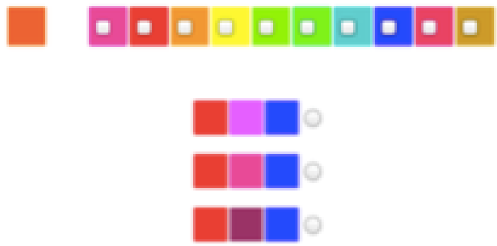

Figure 2.29: Example of Color Set. [GG14b]

A user-study was designed to assess the goals afore mentioned, two sets of colors were created from the model CIE-L*C*h*. The first (set A) had to do with dyadic mixtures, with pairwise combinations between the four main colors (R: Red, G: Green, B: Blue, Y: Yellow): RG, RB, RY, GY and BY. The second set (set B) consisted of triadic mixtures of the referred colors: RRG, RGG, RBG, RYG, RRB, RBB, RYB, RYR, RYY, GBG, GBB, GYB, GYG, GYY, BYB and BYY. The study started with a profiling questionnaire about the users; on the second part, a color blindness detection test was conducted with a simplified 6-plate colorblindness Ishihara Test. On a third part, users were randomly presented with a color from set A or B and were asked to chose from a color palette, the colors which mix into that color, as in the top image on Figure 2.29. After, users were presented to colors blended into HSV, CMY(K) and CIE-L*C*h* and they had to pick the most natural transitions (bottom image of 2.29). The final step was a simple satisfaction questionnaire where users were asked to indicate in a 5-point Likert Scale, how easy it was to find which pairs resulted in the colors given and the most natural blending option.

The study was performed to 73 non-colorblind, mostly middle-aged, all graduated users; the majority (about 64%) was male users and most everyone (96%) lived in Europe. For the set A, the success rates were higher for RY and GY color mixtures, which correspond to smaller angles in the CIE-L*C*h* color wheel, and the worst success rates were consequently to wider angles in the wheel: BY, RG e RB. Respecting set B, results were considerably lower which can indicate that either choosing few colors from a wide palette is confusing or users were not able to correctly perceive the original colors which originated the mixed color; however, the highest and worst rate of success is aligned with the set A, since GYG, GYY and RYY yielded the best results, RRG, RBG, BYB and BYY the worst. Regarding, the most natural transition, users chose CMY(K) as having the smoothest one, followed by CIE-L*C*h* and HSV; despite users attributed to CIE-L*C*h* the second position in natural transition's podium, they found it hard to perceive the colors that were mixed during the study (which were mixed in this color model).

The fact that CMY(K) has the smoothest transition to users is related to what Gosset [GC04] stated, that subtractive color models learned in childhood restricts the mental model of color which users create; in depth research has to be done to compare blending perception between CIE-L*C*h* and CMY(K) models. It should also be take into consideration that, although the sample is large, there is a considerable gap between genders: more women should be included in the study since, as previously mentioned, women can distinguish a larger variety of shades. There is not an extensive cultural representation, just as there is no representation of various educational levels besides graduated users, which could be interesting to show.

Visualizing Social Artifacts

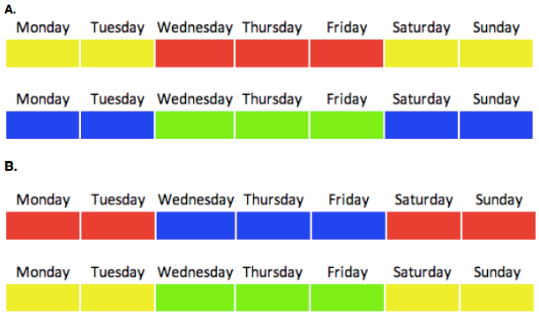

Figure 2.30: Example of Color Combinations. [GG14a]

Understanding the relationship established between colors and social artifacts of the users was another goal of research, which derived from the seed paper [GG14b]. According to the authors, when trying to visualize Social Personal Information (SPI), there are a few relevant concrete aspects for users such as contacts, keywords and ratio between send and received messages; so, color stands again as a resourceful solution, representing different topics with different colors and creating blends. Again, the usage of color blending to social artifacts representation had not been studied yet, particularly the application of colors to different concepts of social and personal facets. In order to understand this, a user-study was conducted [GG14a] to verify: a) which colors pairs were associated to contacts and subjects of conversation, b) which of those pairs were associated with sent and received messages and c) which color features, such as brightness and saturation, were identified with volume and variety of subjects and contacts. The study was crafted similarly to the previous study, having a first profiling questionnaire and color blindness detection, and a set of questions to canvass if users find contacts more relevant in computer-mediated interactions, than topics of conversation. To pursue this, two scenarios were created, A with Red-Yellow and Green-Blue pairs considered, and B with Green-Yellow and Red-Blue; as seen on Figure 2.30, for each scenario, different weekly views from a calendar were created, where users were asked to judge the percentage of message exchanging for each day, the days which had the highest rate of received (over sent) messages and, lastly, the group of days in which a wider variety of subjects were discussed or messages were exchanged with a higher number of people. In the end, a satisfaction questionnaire was given, to perceive if users find it natural to associate colors to social artifacts.

Having 40 responses from from non-colorblind users, all of them had european citizenship and the majority was male subjects (70%). 21 participants could not decide if contacts were more important than subjects of conversation and 18 others have considered contacts to be the most relevant aspect, while a minority thought of subjects to be the most important facet. Gama *et al.* concluded that it exists a strong association between conversation topics and colors within the red color range (either Red-Yellow or Red-Blue), so as for received messages, where users manifestly expressed the red color has to be associated with received messages. This fact is intrinsically linked to occidental color conventions, which states that red color is associated to actions or attention calls and green color is conventionally related to actions who do not require further operation, which can be easily associated to sent messages. In addition, the majority of participants associated message volume with colors with lower brightness (*i.e.* darker colors) and highly saturated colors to a wider scope of contacts and topics.

The bottomline of this study concludes that users did not find particularly natural to associate colors with these social artifacts. These artifacts were tested in order to create a set of guidelines for a concrete system; perhaps, other artifacts could have a different responses and acceptability, and users could easily recognize associations between colors and artifacts. It should be considered that color perception is influenced by cultural patterns and standards, so an extensive cultural study should be considered.

Perception of Relative Amounts of Color

Humans can perceive the original components that created a particular color: the final study performed by Gama *et al.* relating Color Blending Perception investigated precisely, the extent people can perceive relative amounts of color components in blended colors [GG14c]. However, the amount of each component may not be evident: as it has been said before, there are pairs of colors which yield better results than others due to cultural standards, conceptual models or simply color conception. Color blending has one major handicap: although it reduces the cognitive load by associating familiar colors to information, it may not show the expected accuracy if we do not understand human color perception.

To fulfill this problem, it was designed a user-study similar to the previous ones, consisting of a first profiling phase, a color evaluation step and a 5-point Likert Scale to describe how easy it was to decide the amount of each color component in the given color. Respecting the color evaluation step, it was created a set of 10 interpolated colors for 4 pairs: (Red-Yellow), (Green-Yellow), (Green-Blue) and (Red-Blue), as seen on Figure 2.31. Then, users were presented with each of the 40 blended colors individually and asked to rate these from 1 (only the first color component) to 10 (only the second color component).

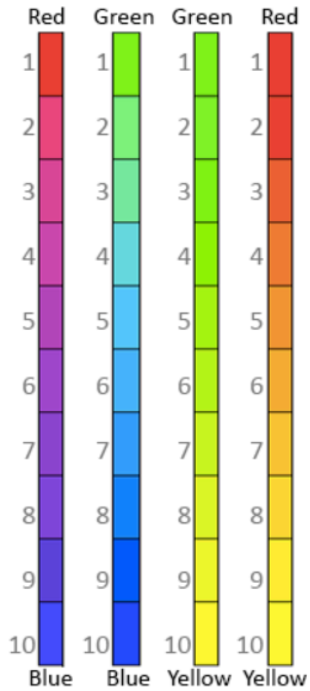

Figure 2.31: Pairs of 10 interpolated colors. [GG14c]

20 participants have attended the study, equally divided by genders, non-colorblind and all european citizens residing in Europe. Users happen to perceive most colors correctly regarding the pair (Red-Yellow) and likewise colors in both extremes, even for other pairs: "central colors" are generally the most problematic. An important conclusion from this research is that it should be considered, at maximum, 5 colors when blending colors, so that the relative amount of each color component is perceivable by the users. Results have shown, also, that subjects found it moderately easy to perceive color component weight in blended colors.

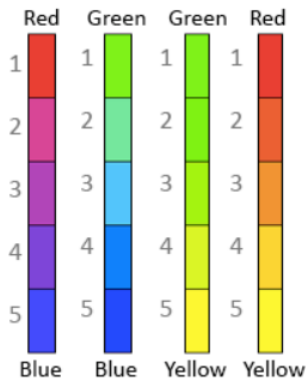

Figure 2.32: 5 Step Scales. [GG14c]

This study provides us several rules of thumb for crafting an information visualization or a color blending perception: when the idea is to provide rough information, color information may be successfully used; be that as it may, no more than three interpolations must be done between color pairs, so humans can distinguish different component weights. Hence, a set of 5 colors is the optimal solution: 2 pairwise colors and 3 interpolations, as on Figure 2.32.

Other investigation

Apart from the previous referred studies, it is possible to give some examples of current work that already uses color blending techniques. For example FiftyThree®, the company which created the App for drawing on tablets called "Paper", put a lot of effort on reinventing the color mixer to transmit a complete color blending experience which neither lacked realism or was too realistic[30]. FifttThree's team of developers manually selected 100 pairs of popular colors and tested them to understand which pairs created the best blends. In the long run, the team wanted to have a complete perceptual-constant, touch-native mixer, capable of creating harmonious mixes between colors chosen by the user. Initially, they used the HSV Color Model but it was not working out correctly, whereby it was explored color systems in which changes in hue, saturation and lightness were perceptually even. In the end, FiftyThree® produced a color mixer in which you mix a color from a palette with a previous one, gently swiping in circles to increase or decrease the mix.

Obviously, there are some bad examples which represent mistakes in choosing the appropriate color palette or scale, not taking into account the area that would represent color. An example of such bad example is a representation of the educational achievement and the median income on the United States of America, in order to perceive in which states people are going to school, where the are earning money and if there is any correlation between these variables[31]. However, the problem lies on the colors chosen to represent each variable: there were picked colors from the CMY(K) color model and they were mixed to convey information of three different variables at the same time; the problem in Figure 2.33 is such that it is almost impossible to tear apart perceive amounts of original colors since it is not provided an appropriate color scale and it is quite difficult to distinguish darker colors near purple, dark green or black.

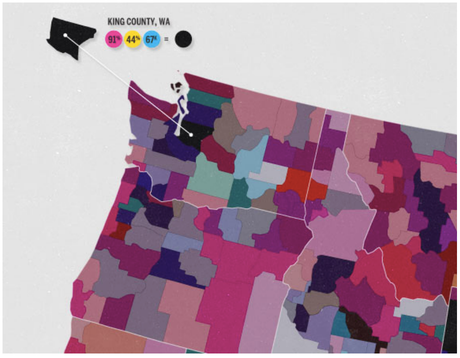

Figure 2.33: Bad Color Blending Usage.[31]

Joshua Stevens presents[32] an acceptable solution for the problem of mixing colors that apparently do not correlate, mixing two colors (instead of 3, as the previous example) that are supported by 3-step scale each one, and combined create a 9-step scale in which each step can be perceived discreetly. The author provides advises that bivariate data can be complicated if not shown in a clear way, and indicates that the legend for a map in which color blending is used should not use many decimal numbers and use only the strictly-needed labels, lowering the cognitive load of the user. This work can be seen in the Figure 2.34.

As seen, color blending can help conveying information but, at the same time, it can undermine the accuracy of the perception if too many variables are shown at the same time, or even if there exists scales with too many interpolations. Some techniques have been under research to provide a curated approach to color perception tasks, which can be combined with color blending also.

[30] "The Magical Tech Behind Paper For iPad's Color-Mixing Perfection". Available at: http://www.fastcolabs.com/3002676/open-company/magical-tech-behind-paper-ipads-color-mixing-perfection. Accessed on 2015/11/06.

[31] "Reading, Writing and Earning Money". Available at: http://awesome.good.is/transparency/web/1101/census-data/transparency.jpg. Accessed on 2015/11/06.

[32] "Bivariate Choropleth Maps: A How-to Guide". Available at: http://www.joshuastevens.net/cartography/make-a-bivariate-choropleth-map/. Accessed on 2015/11/06.

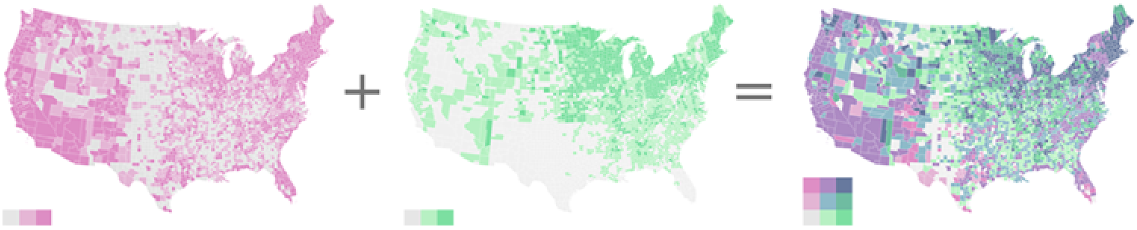

Figure 2.34: Choropleth Maps.[32]

2.4.2 Color Blending Alternatives

Color Weaving

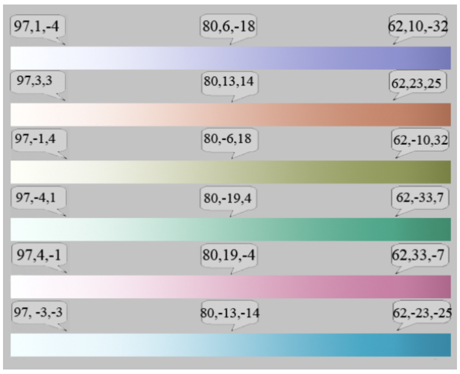

Figure 2.35: Data variables. [HSKIH07]

One of the challenges of multivariate visualization is to clearly show different layers of information with color patterns, with no doubt to the user: as composing different layers on top of each other, most of the time it creates colors and patterns which do not have direct or significant meaning. Urness *et al.* proposed new insights and introduced new techniques for using color and texture in a effective way, to convey information about two-dimensional scalar and vector distributions [UIM03]: beside other techniques, the authors have introduced the concept of color weaving, a color blend technique that presents original colors separately, composing a colored mesh with a fine-grain texture. Comparing to the tradicional color blending, the latter is a simple flat color used to illustrate the mix of different entities with different values, whereas the new one combines multiple scalar single-hue-encoded distributions, computed over a common field, to form a multi-colored line integral convolution tapestry, in which multiple color combinations are represented explicitly via adjacent lines in a texture, rather than overlaying multiple layers of single color.

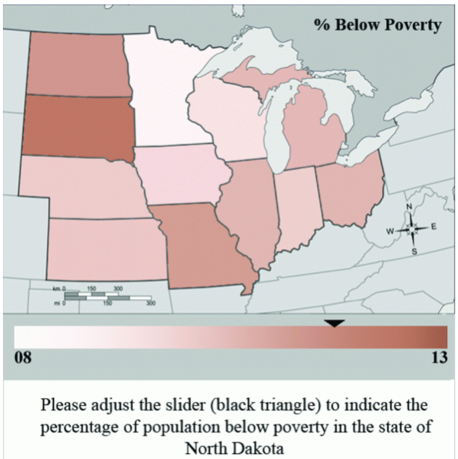

Figure 2.36: Example of a Map. [HSKIH07]

This technique was vastly studied by Hagh-Shenas *et al.* [HSKIH07]. These researchers created a set of three experiments, in which the user was questioned over a state map of U.S.A., reading it and giving answers that would be statistically analyzed.

The goal of the **first study** was to test the capability of precisely reading and understanding numerical data based on color intensity. Each state of U.S.A. had a single color, which identified the percentage of a given data distribution, from 6 possible; each variable in test had a color scale from white to a particular color (Figure 2.35). It was considered eventual factual knowledge, so the information was mixed between states. The test methodology included configuration of parameters like background color of the test, the distance to monitor, its resolution, the width and height of the screen and maps. The user was presented to a map, a question and a slider to match the color which was asked to found in the map (Figure 2.36). There were a total of 9 graduates, undergraduates and academic staff participants, 3 females and 6 males and they were compensated 5 dollars per half an hour for completing the experiment; the results turned out to be uniformly accurate.

Regarding the **second study**, the goal was to quantify differences among three conditions for visualizing multivariate data when variables overlap in a region. Again, a map of 12 states of the U.S.A. was showed, randomly presenting different combinations of variables, via color-blending where colors were made semi-transparent and then overlaid to form a single composite representation (these colors were equivalent to averaging the CIE L*a*b* values of the individual overlapping colors), or via color-weaving, in which the separate color layers were individually sampled at independent pixels defined by a random noise function, and then stitched together to form a fine-grained textured mesh representation (Figure 2.37). For color-weaving, it was tested out small and large possible textures. Since the number of possible combinations of variables and types of color representation is high, not all displays were shown and not every state was tested, only Iowa, which can limit user perception and influence results. 18 users attended the study, 4 females and 14 males from different colleges. The authors concluded, with this study, that:

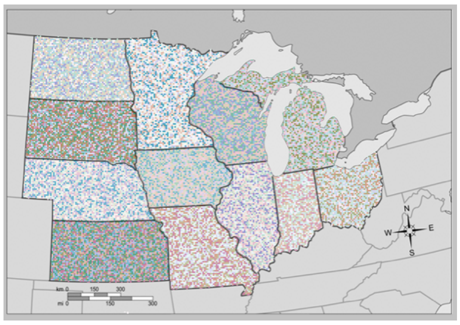

Figure 2.37: Example of a Map. [HSKIH07]

- The error rate is quite lower when the original color information was presented in the mixture, than when colors were blended.
- Either color-blending and color-weaving do not yield accurate results when six variables are mixed ate the same time.
- Color-blending is considerably less precise than color-weaving.
- Color-blending and color-weaving have a common problem: the background color and the surrounding color can change the appearance of a color, due to a perceptual process called assimilation, in which small color areas appear more similar to their surroundings.

Finally, the **third study** aimed to explore the effects of hue separation and luminance difference on the error rates in viewers' judgment of values of individual components. Specially, these two questions: 1) will error rates be larger, smaller or the same of reading color combinations where the hues are separated by 60, 120 or 180 degrees in the CIE L*a*b*? and 2) will this rates change by reading color combinations where the luminance values of individual components is equal, close or widely separated? To address this, a total of 180 displays were created by combining, with noise functions or blend, all possible combinations of two colors from the six used before, creating 15 combinations which were matched with three lightness pairs: one at *(L=72 and L=76)* - a closer -, the second at *(L=68 and L=80)* - a moderately close - and a third one *(L=64 and L=84)* - a more widely separated. The task itself was very similar to the second study. To this study, only 4 (2 females and 2 males) students attended, which compose a very small sample. Even so, it was concluded that the performance increased significantly when luminance values of each color were similar to each other; it was also found a significant main effect of luminance difference in all cases except where the hues were directly complementary.

These studies concluded that the technique of color weaving is substantially more effective than color blending, for multivariate visualization; combinations of 2, 3 or 4 different data variable remain error rate low, but with 6 the rate begins to rise. It was not found any significant advantage, for both color blending and color weaving, in using more separated hues in CIE L*a*b*. Finally, a relevant conclusion of this study is that hues and luminance play different roles, since the observers estimate the lightness value of each variable in question and hue is only used for distinguishing the variables from each other.

Hue-Preserving Color Blending

Transparency is almost indispensable when visualizing three dimensional structures, since it is one way to alleviate the observer's visual barriers. In 2009, Chuang et al. tried to combine color and transparency when visualizing volume information, introducing the idea of preserving the of preserving the hue of the original color when blending [CWM09].

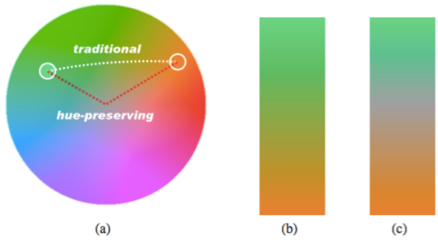

Figure 2.38: (a) Regular and Hue-preserving color blending. (b) Traditional alpha blending between teal and orange. (c) Hue-Preserving color blending between teal and orange. [CWM09]

Perceptual transparency is not identical with physical transparency, which is typically the starting point in computer graphics. Perceptual transparency is the perception of an object being in front of another background object; on the other hand, physical transparency is affected by many aspects such as luminance, apparent motion, subjective contours, and figural organization (size, shape, etc.). Particularly, this last one influences the before-seen Gestaltism. Since the target of their research was perceptual transparency, the authors created an approach that is not subject to any type of physical constraint, but can be formulated as an algebraic model.

Starting from the work on perceptual psychology (some of this is already covered in this document, the remaining is present in the referenced document), they have reached a set of design criteria that lead to an equation which expresses the color addition in Hue-Preserving color blending:

$$C_{new} = C_1 \oplus C_2 \tag{2.4}$$

There were some requirements that Hue-Preserving sum had to meet:

- The luminance of $(C_1 \oplus C_2)$ should be identical to the sum of the luminance of C1 and C2.
- The hue of C_{new} is either equal to the hue of C1 or C2: $Hue(C_{new}) \in \{Hue(C_1), Hue(C_2)\}$. The hue of C_{new} is chosen as the dominant hue of the two colors C_1 and C_2. The dominant color is the one whose hue would be closest to the blended color in traditional color summation. When the dominant color, and thus the final hue, is to change, C_{new} should go though the gray point with vanishing saturation, so that even an abrupt change of hue does not imply a discontinuity in chromaticity, as seen on Figure 2.38.(c).

The goal of modifying the sum operator is that, when two colors are mixed, the resultant color only contains the hue of one of the mixed colors, the dominant one. This technique can be divided into two pieces, either occurring one or another:

- The blending from one input color C_1 towards the gray axis, keeping the hue of C_1.
- The blending from the other input color C_2 towards the gray axis, keeping the hue of C_2.

The hue from the dominant color does not change: it is the hue from the non-dominant that is modified (but only the saturation and luminance) until it reaches a complementary color to dominant. By adding the opponent colors, the mixing moves towards the gray point and it is guaranteed that the original hue does not change; this also guarantees that this method generates exactly the same result as the tradicional blending, when mixing opponent colors. However, there are some disadvantages: gray colors in hue-preserving blended images can be confusing as gray can come from blending various hues (as on Figure 2.39), and this technique of blending colors is order-dependent, since blending colors in different blend orders can produced different results. Also, this technique is based on RGB and a future work could implement hue-preserving blending on different color systems.

Figure 2.39: Example of a Regular Color Blending *versus* Hue-Preserving Color Blending. [CWM09]

Augmented-Reality Color Blending

Recent research about augmented reality (AR) displays have shown that mixing illumination, background color and virtual graphics have an impact on usability and in user performance. In many cases, the outdoor environmental conditions can dramatically affect users' color perception of user interface elements, by washing out text or icon colors. Gabbard et al. presented their experiences in creating an AR testbed that emulates outdoor lighting conditions, which allows them to measure the combined color of real-world backgrounds and virtual colors, as projected through an optical see-through display [GZSW10]. This does not constitute an alternative to color blending, but a formalization of a color blending model in augmented reality.

In a long-run, the goal is to create a mathematical model which allows to anticipate which color will be perceptible to the user, after all the spaces interact; such model is useful to predict, in real-time, what color will reach a head-mounted display (oHMD) user's eye. The display uses the RGB color model and the oHMD uses Adobe RGB gamut, which is larger than regular RGB, including more visible green and cyan colors. To examine real-world background colors, it was used a version of CIE model, CIE 1976 which includes a definition of CIE L*u*v* color space.

The process of perceiving a computer-generated colored graphic on a oHMD on a different background can be described as seen of the Figure 2.40. A light source produces light with spectrum L_1. the light L_1 hits a surface with background reflectance B, producing reflect light:

$$L_2 = RF(L_1, B) \tag{2.5}$$

The function RF represents how surface reacts to reflected light (related to surface reflectance physics) and B the reflectance of the background. L_2 enters the front of the AR display, where it

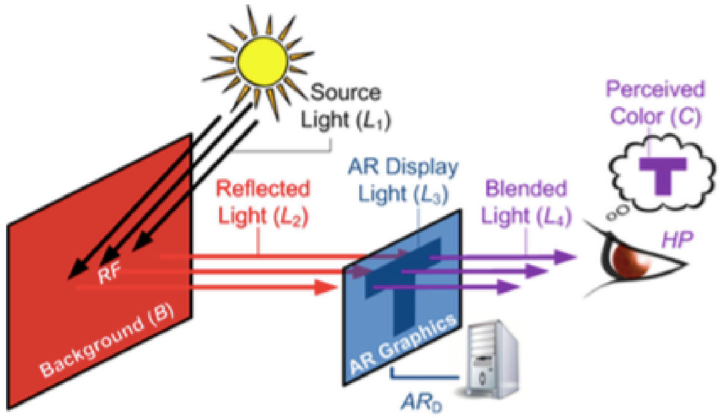

Figure 2.40: A formalization of Color Blending in oHMD. [GZSW10]

is mixed with the AR display light L_3, producing:

$$L_4 = AR_D(L_3, L_2) \tag{2.6}$$

AR_D is the function that characterizes the entire display, parameterized by a particular display system indicated by the subscript D. Finally, the blended light L_4 enters the human eye, being perceived as

$$C = HP(L_4) \tag{2.7}$$

HP is the Human Perceptual System. The final equation can be described as:

$$C = HP(AR_D(L_3, RF(L_1, B))) \tag{2.8}$$

As future work, the authors intend to investigate the contributions of the L*u*v* components and conduct a user-study to verify if the vast acquired laboratorial results match users' expectations and perception.

2.5 Discussion

The goal of this research is to understand how people perceive the blending of particular colors and if perceived, in which terms do they understand the blended color. We have conducted an investigation to realize what is related to the act of perceiving color and how it is judged.

The usage of color blending is hugely related to the fact that color is great to convey information and messages, but there has not been quite an extensive analysis about how people react to blends of color, having in mind also cultural patterns which could be tested. Gama and Gonçalves have tested the color blending for Data Visualization [GG14b], concluding that users can detect mixtures with higher success rates for colors which represent to smaller angles in the CIE-L*C*h* color wheel, but users found it hard to perceive the colors that were mixed during the study. The users also chose the CMY(K) Color Model as having the smoothest transition of color. It should be take into consideration that, although the sample is large, there is a considerable gap between genders, which should be more well balanced in future work.

The lastly cited authors also studied if users can address different concepts of Social Personal Information to colors [GG14a]; they concluded, for example, that it exists a stone association between conversation topics and colors within the red color range, so as for received messages, which is intrinsically related to occidental color conventions, that state that red color is associated to actions or attention calls. On the other hand, Gama *et al.* tested how the users perceive relative amounts of color [GG14c], realizing that they happen to perceive most colors correctly regarding the pair (Red-Yellow) and other extreme colors, and at most 5 colors should be presented to the user when blending colors, so that the relative amount of each color component is perceivable by the users. However, in none of the studies were considered cultural differences and standards and the sample of users was quite reduced to European citizens living in Europe. In further studies, a larger sample should be considered.

Finally, there were studied some alternative techniques to color blending which could be further tested, such as **Hue-Preserving Color Blending and Color Weaving**. In this technique, a textured mesh presents the original colors that were mixed to create a resulting color, using a Noise function to create the pattern in which the relative amounts of colors were represented. The original studies conducted by Hagh-Shenas [HSKIH07] were not constant, since in the first study there were a total of 9 graduates who attended, in the second study it rises to 18 users and in the third one, only 4 users participated; this represents a threat to the study, since it is a very restricted and small sample. Hagh-Shenas *et. al* created a large number of displays and they were not able to test all of them. The ability of testing everything, while not crafting long and exhaustive tests should be considered in future work.

Chapter 3

Research Proposal

Contém o que vai ser feito e como. Deve ter máximo 5 páginas

Chapter 4

Evaluation

Estatísticas, que análise a-la IPM vai ser feita (t-Student, etc). Mostrar que se conhece bem como se vai tratar dados. Contem tudo o que vai ser extraído e como vai ser tratado. Maximo 1 pagina.

Chapter 5

Planning

Gantt Chart com ponto de situação, o que foi feito e o que vai ser feito próximo semestre. Meia página.

Chapter 6

Conclusion

Conclusões, devem dar origem a meia página também.

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