Will It Blend?

Studying Color Mixing Perception

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Abstract

Using color to convey information is not a recent rule: its usage is further associated to standards, statistics and computer science. However, color is a subjective aspect of human perception, as it is strongly influenced by cultural background, childhood learning and possible existent color vision deficiencies. Over the last years, research has been made to ascertain if color is the ideal channel to transmit information; particularly, if the blending of two or more colors can convey, in a efficient way, the information contained in two or more variables, using color blending techniques.

Nonetheless, previous investigation has not come to an agreement about to which extent can color blending techniques be used, in an efficient and effective way, to convey information.

We intended to study if the users can detect the blending-basis when the result of a given color mixture is given, and vice-versa; moreover, it was important to understand which color model has the best matching with the user's blending expectation, and detect colors which may yield better results than others.

We have found that CMYK is model that best resembles the users' expectations, while the orange, green and yellow color-blending results are the ones which generate shorter distances to between the reference colors and the ones indicated by the users. On the other hand, the CIE-L*C*h* Color Model is the one which is farther apart from the users' mental model of color. We have also detected that there is a mild indicator that it exists a difference between the responses from Female and Male users, but only in a few color blendings. All the data collected was developed through a user study with 259 users, from different genders and ages, which was supported by an online user studies platform called *BlendMe!*.

As product of this Master thesis, we collected a set relevant implications of using color blending techniques, in the Information Visualization field of research. Additionally, we provided a set of questions apart from the ones answered by the us, which remain unanswered and could turn out as an interesting source of future work, and a cleaned dataset containing the data collected from the user study which could be further analyzed by other researchers.

Keywords: colors, models, spaces, blending, InfoVis, color perception, user study, calibration, scales, organization, data visualization, data processing, blending techniques, color vision deficiencies, demographic analysis

Resumo

A utilização de cores para transmitir information não é uma técnica de origem recente: está fortemente associada a standards e nomenclaturas de acordo com cores, apresentação de estatísticas e contagens de dados, para além da óbvia ciência da computação. Contudo, a cor é um aspecto consideravelmente subjectivo da percepção e interpretação humana do meio que nos envolve, já que é fortemente influenciado pelas raízes culturais, pelas aprendizagens obtidas na nossa infância e, também, por possíveis deficiências que existam no sistema visual humano. Ao longo dos últimos anos, tem sido realizada investigação que incide num melhor conhecimento sobre se a cor é, de facto, o melhor canal para se transmitir informação; particularmente, se a mistura de duas ou mais cores pode transmitir de uma forma capaz a informação de duas ou mais variáveis ao mesmo tempo, recorrendo a técnicas de misturas de cores.

Ainda assim, a investigação realizada até agora revelou-se inconclusiva no que toca à utilização destas mesmas técnicas. Assim, o objectivo da nossa investigação é estudar se os utilizadores conseguem detectar as bases de uma mistura de cor quando lhe é fornecido o resultado da mesma, e vice-versa; revela-se, também, importante perceber que modelos de cor oferecem um melhor mapeamento da expectativa de mistura dos utilizadores, detetando se existem cores e misturas de cores que originam melhores resultados que outras.

Concluimos, entre outros temas, que o modelo de cor CMYK é o que melhor retrata as expectativas de mistura do utilizador, enquanto que o laranja, verde e o amarelo são as cores que originam distâncias mais curtas entre as cores de referência para cada mistura citada, e as indicadas pelos utilizadores. Por outro lado, o modelo de cor CIE-L*C*h* é o que se distancia mais do modelo mental de cor dos utilizadores. Detectámos também que existe uma ligeira diferença nos resultados indicados pelos utilizadores femininos e masculinos, mas apenas em algumas misturas de cor. Todos os resultados foram recolhidos com base num estudo realizado com 259 utilizadores de vários géneros e idades, o qual foi suportado por uma plataforma de estudos de utilizador *online* denominada *BlendMe!*.

Como resultados desta Tese de Mestrado, retirámos algumas implicações relevantes sobre o uso de técnicas de mistura de cor, na área de *Information Visualization*. Adicionalmente, chegámos a um conjunto de questões (para além das por nós respondidas) que ainda não encontraram a sua resposta, e que se podem revelar objecto interessante de investigação no futuro, bem como um conjunto de dados já tratados que podem ser analisados por outros utilizadores.

Palavras-chave: cores, modelos, espaços, misturas, InfoVis, percepção de cor, estudo de utilizadores, calibração, escalas, organização, visualização de dados, processamento de dados, técnicas de mistura, deficiências de visão de cor, análise demográfica

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Chapter 1

Introduction

Color can inspire, affect your mood, influence your attitude and change your opinion. It has been associated to brands, constituting 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: Starbucks® has a strong connection to Green, Target® to Red, UPS® to Brown, Wimbledon Championships® are strongly associated to Purple and Green and Facebook® to Blue.

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*.

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 fluctuate 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.

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 evolved generations.

Hence, creating colors standards was more than a need, creating rules for the color usage across different areas of our society. 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, consequently, determining the spectrum of colors which is human perceivable. The colors are combined and represented by Color Models (*e.g.* RGB, HSV or CMYK) which have their own color gamut: the combination of all these gamuts could be represent in a Color Space like CIE-XYZ, which maps all the human perceivable colors in a Chromaticity Diagram, frequently named as a Horseshoe Diagram given its shape.

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 an appropriate *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, using a technique of *Color Blending*, conveying exactly the same information but, from a Computer Graphics perspective, in an 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 researched if the blending of colors for data visualization [GG14c] 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 [GG14b], 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 users capable of distinguish when blended?

Some researchers have developed parallel techniques which use Color Blending in different ambits, such as blending colors forming stitched patterns, improving the perception of originally mixed colors [UIM+03], or methods to create colors that naturally mix without confusing colors to user [CWM09].

Even though investigation has been done, there are flaws and situations raised from them which remain to be fully tested and understood. These led us to state that reseach goal as:

Study if color blendings can be detected by the users, while testing if it is easier for users to estimate the pair of colors that resulted in a particular given blend, or reciprocally, to estimate which blend will result from a given pair of colors.

Additionally, we believe that it would be interesting to **observe if there are any color blendings which may yield better results than others**, and **infer if the users follow some kind of mental convention and organize the color when conveying the answers**, formulating possible implications of color blending usage, in InfoVis field.

Having the goals stated, we decided to conduct a user study to fulfill them and answer a small set of objective questions; this color study had to be realized in a controlled environment where all calibration details were validated to ensure a correct visualization, and also in an online environment, since it was mandatory to gather the largest user sample possible to corroborate the laboratory results.

We have decided to develop a platform which would be capable of dealing with laboratory and online data: this way, the overhead of analyzing data from two different environment would be reduced and data was concentrated in the same place. The study should be divided onto four important phases: **User Profiling Phase, Calibration Test Phase, Color Vision Deficiencies Test Phase** and, finally, **Core Test Phase**, which is when we present the color blendings to the users. These phases are important since full coherence between all user data is a major concern.

It was created a set of color blendings based on the primitives from the RGB and CMYK Color Model: Red, Green, Blue, Cyan, Magenta and Yellow. This set was formed by blendings of two and three colors, having the first ones been tested, either by being given the result of the color blending to the user and asked for the basis, or by giving the basis and asking for the result which the user though it would be appropriate. These colors were blended following the HSV, RGB, CMYK, CIE-L*a*b* and CIE-L*C*h* Color Models, interpolating the colors from each pair accordingly.

In the end of the study, we analyzed the data and divided the results according to: environment, color models, age groups and gender groups, and deficient and non-deficient color vision users. The analysis of this groups was also supported chromaticity diagrams, which depicted the answers-pairs and reference answers mapped according to the standard CIE-XYZ. The analysis revealed that the color blending which constantly yielded the best results across all color models is the **mixing of Red-Yellow,**

to achieve Orange, while the mixture which provided the worst results when evaluating the distance from the user's answers and the ideal answers, is the blending of **Green-Magenta, resulting in a Blue shade**; these results are consistent with the fact that the human color perception is conditioned by the amount of Cones present in our eyes.

When analyzing the answers by Color Model, we can observe that the CMYK Color Model is the one which presents the best results across both study environments, while the CIE-L*C*h* Color Model is the one which typically provided the worst results across all color blendings. We have also found that, for color blendings which involved the Red color there was, in fact, evidence that the users sort the colors when indicating the blending-basis, revealing some mental color organization.

We have found some research opportunities along the analysis, namely evaluating the answers which came from uncalibrated users because it could show us how resilient the user's expectation is to calibration changes, and explore the answer-pairs which contain one white component which could reveal that either the user did not know how to blend the colors, or did use the white answer to lighten the color given a bit.

The focus of this Master thesis was to conclude relevant implications of using color blending techniques, in the Information Visualization field of research, which are going to be discussed later on this document.

1.1 Contributions

This dissertation aims to provide useful inputs about how color blending can be correctly used in Information Visualizations, and according to the users' expectations, leading to the following contributions:

- A set of results which determine the answers to the aforementioned questions, obtained with online and laboratory users. These results are organized in tables, divided according to each type of environment and users' condition, and are already cleaned and ready to be used.
- A user studies platform called *BlendMe!*, which is composed of four test phases, helping the process of creating a user profile, testing the calibration of an LCD Display, evaluating the presence/absence of color vision deficiencies and collect user feedback. Currently, the main core phase of the study is aimed to evaluate 32 questions about color blendings, but it can be easily changed.
- A compendium of guidelines on how to use color blending in Information Visualization, produced based on users' results, establishing aspects about color models and blendings which provide the best results.

1.2 Dissertation Outline

The rest of this document is organized as follows: Chapter 2 provides simultaneously a theoretical background on the color theory and the research realized on the related work previously accomplished in this research area, Chapter 3 presents the design and implementation of the *BlendMe!* platform, Chapter 4 explores the results' analysis and diagrams, discussing these results and presenting possible implications for InfoVis. Finally, Chapter 5 concludes the entire thesis document, briefly talking about the limitations found, introducing some ideas for future work.

All the implementation files, analysis scripts, generated outputs and other research-related documents are contained in the public *GitHub* repository: `github.com/pdegarcia/blendingbox`.

Chapter 2

Background

In this work, we introduce a review through the topics related to this project. We start by introducing an explanatory view about Color Perception, narrowing it down to Color Philosophy and the Human Eye. 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. In the end, we will discuss the results found from this investigation was draft research questions which remain unanswered.

2.1 Theoretical Background

This section contains the research performed to ascertain the theoretical background which supports our investigation. We will begin by analizing the concepts Color Perception, then briefly explaining the differences between Color Models and Color Spaces.

2.1.1 Color Perception

In this section, we overview the philosophy about color, relating real-world perceptions to human perception through the eye. There are two main areas of interest, called the Cones and the Rods, which will be explained with quite detail; these areas restrict how we perceive color, specially if there are visual deficiencies. Moreover, color creates mental models and codes, which are part of routines and rules followed by society, and will be exemplified in the end of this section.

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[1], concerning the physical and psychological 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 1739 [Hum39] 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

[1]"Stanford Encyclopedia (...)", Available at: `www.stanford.io/1MWp7Zh`. Last accessed on October 17th, 2016.

recently argued [Chi14] 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 instantaneously, 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, we can derive more theories: **Primitivism**, **Reductive Physicalism**, **Dispositionalism**, among others.

Chirimuuta [Chi14] also compares the **Realism** against the **Anti-Realism**, since in the last one, 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 by the anti-realists 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, 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.

2.1.2 The Human Eye

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. 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, then, decodes light energy into neural activity: this light reaches the eye through the **cornea**, crosses the pupil and is refracted by the lens, coming to a final projection of a sharp image in the back of the eye, the **retina**. However, this 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.

In order to be rearranged, the light is converted 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 absorption of photons in their proteins; cones are concentrated in the **fovea**.

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. After all, the brain digests the signals sent as 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 [Att54], we cannot make predictions about anything, based merely on the present visual field, but also depend on previous - and, for that, familiar - visual fields.

As covered before, 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**.

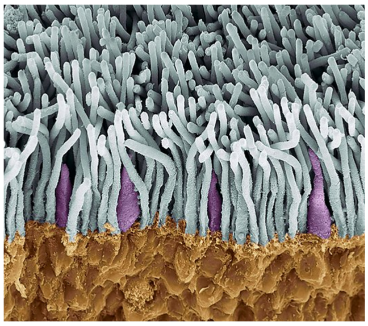

Figure 2.1: Cones and Rods.[2]

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 completely instrumented by them. They can be seen on Figure 2.1 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. 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.

- 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 derived from the three types of cones, allows the brain to perceive a continuous range of colors. The distribution of the amount of each type can differ.

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 2.1); 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 (this is why your ability to see gradually increases in the dark). This limitation in the types of rods is the reason why they cannot discriminate colors, as the cones. On Figure 2.2, it is possible to compare the light absorbance for different wavelenghts, distributed among Cones and Rods.

[2] "The Human Eye and Adaptive Optics", Available at: `www.bit.ly/1zMEgK6`. Last accessed on October 17th, 2016.

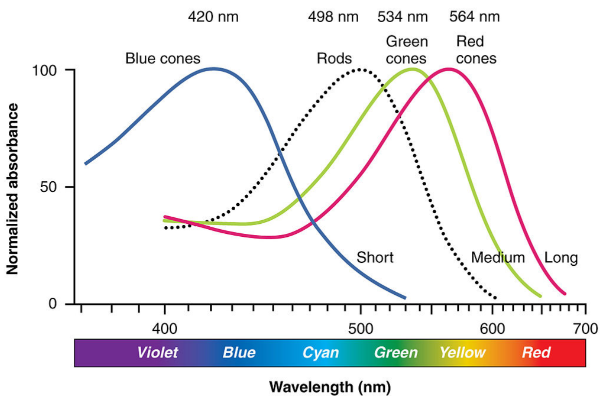

Figure 2.2: Diagram of Eye Color Sensitivity, depicting distribution between cones and rods.[3]

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.

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 the so called **Trichromatic Theory**. No single cone can detect by itself the color of a source of 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 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[4]. 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. 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. However, it has to be considered the case in which these cells are totally or partially absent.

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 less than three types of photospins 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, chemical exposure or simply aging can lead to color recognition loss: some of these factors include diabetes, leukemia, Parkinson's disease

[3]"Photoreceptor Cell", Available at: `www.bit.ly/1VNZQHE`. Last accessed on October 17th, 2016.
[4]"How to See Impossible Colors (...)", Available at: `www.bit.ly/1ZdtSKv`. Last accessed on October 17th, 2016.

or Alzheimer's disease. These deficiencies can be classified as **Monochromacy**, **Dichromacy** and **Trichromacy**. We would like to empashize the second type: 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, which figure 2.3 presents:

- Protanopia (from the Greek *prot-*), refers to the absence of red retinal photoreceptors. Protans find 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.

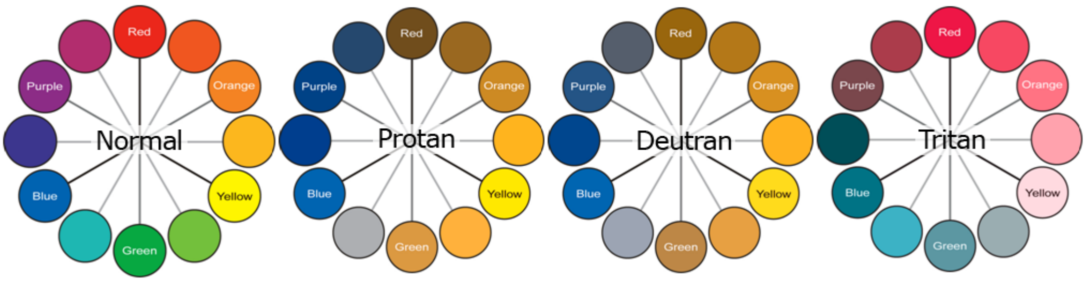

Figure 2.3: Correspondence of Colors Between Normal Vision, Protanopia, Deuteranopia and Tritanopia.[5]

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 2.4. The user is asked to look at the plate with the figure and distinguish the number/figure: if it is correctly spotted the number, the subject does not have a particular type of deficiency; if some difficulty is found, that constitutes an evidence of possible color blindness. 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 various researches about color perception.

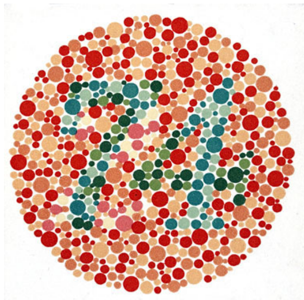

Figure 2.4: An example of a Pseudisochromatic plate.[6]

Mental Models and Codes

Whether agreeing or not on it as an intrinsic existing characteristic, we perceive color on every subject we look at. In fact, one of the things you are taught by your relatives and educators is the concept of painting with color pencils, gouaches 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. 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.

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 [Nat68], 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

[5]"What About Color Blindness?", Available at: `www.bit.ly/1O7IK4G`. Last accessed on October 17th, 2016.
[6]"Ishihara Color Test", Available at: `www.bit.ly/1jp31m3`. Last accessed on October 17th, 2016.

every country should follow; other examples of color standards are the International Maritime Sinal Flags [AM03] (used on ships to transmit messages) or to electrical wiring conventions, among many others.

Color is even perceptually different among different countries, continents, environments and genders: as is know by now[7] [GJH11], 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 the difference between genders is a certainty. In 2011, BBC shot a documentary[8] 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 2.5), to the Himba tribe from Northern Namibia. Surprisingly, they were able to detect a larger number of shades of green 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 2.5: Example of a Green Color Test made.[8]

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 the real-world colors in discrete values.

2.1.3 Color Models and Spaces

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.

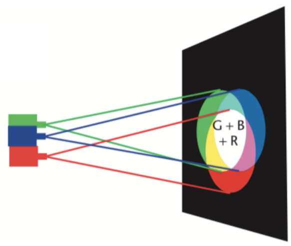

Figure 2.6: Color-matching setup. [War12]

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.

[7]"Where Man See White (...)", Available at: `www.bit.ly/1AMHgcW`. Last accessed on October 17th, 2016.

[8]"It's Not Easy Seeing Green". Available at: `www.nyti.ms/1S71yVo`, Last accessed on October 17th, 2016.

Color Fundamental Concepts

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

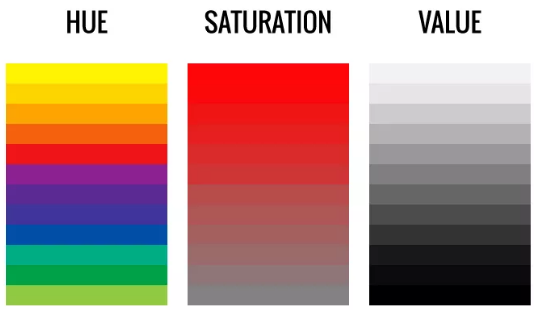

Figure 2.7: Comparison between Hue, the concept of Saturation and Lightness (or Value).[9]

Hue As defined in **CIE Color Appearance Model of 2002** [MFHL02], 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 colors known as unique are only four: Red, Green, Blue and Yellow. The concept of Hue is represented in Figure 2.7, on the left column.

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 turns into gray. For example, in Figure 2.7, 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 2.7): 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 lightness 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.

[9] "How to Analyze Data (...)", Available at: www.bit.ly/1KHHtg2. Last accessed on October 17th, 2016.
[10] "Color Luminance", Available at: www.bit.ly/2203vdp. Last accessed on October 17th, 2016.

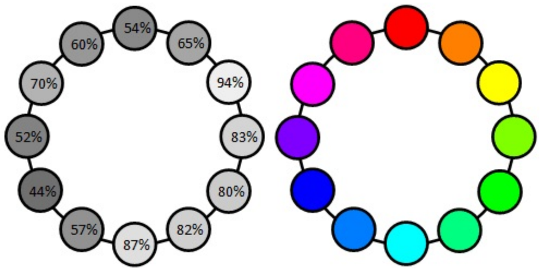

Figure 2.8: Luminance schematic.[10]

Luminance It is a measurement of light, which assesses 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 2.8 describes the percentage of white that each hue contains, being white the maximum percentage of 100%.

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 concepts 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.

Defining Color Models

The concepts of *Color Spaces* and *Color Models* are often confused but, in fact, they do not present the same idea (although they do use similar conceptions). Color models exist to mathematically conceive a description of color, in which color spaces will be based and present the equivalent colors. 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.

A color model is a mathematical description of color, which is substantively different from a color space: the latter represents the gamut of colors described accordingly to the primitives of a color model, containing not only visible colors but also colors that are impossible to represent on physical devices.

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].

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.

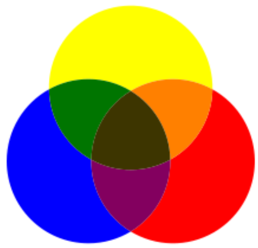

Figure 2.9: RYB Model.[11]

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 and it was necessary to specify a new model which would create a standard in representation of images on digital display devices.

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

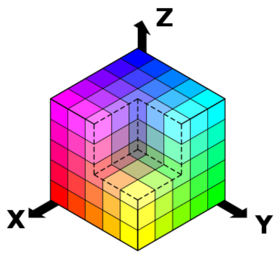

Figure 2.10: RGB Model.[12]

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

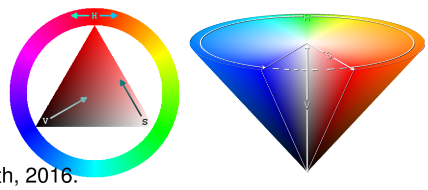

Figure 2.11: HSV Model.[13]

[11] "RYB Plano", Available at: `www.bit.ly/22MHzPJ`. Last accessed on October 17th, 2016.
[12] "RGB Cube", Available at: `www.bit.ly/1n5QCdZ`. Last accessed on October 17th, 2016.
[13] "Computer Graphics (CS 4300) (...)", Available at: `www.bit.ly/1OQh8Vh`. Last accessed on October 17th, 2016.

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**.

CMYK CMYK 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.

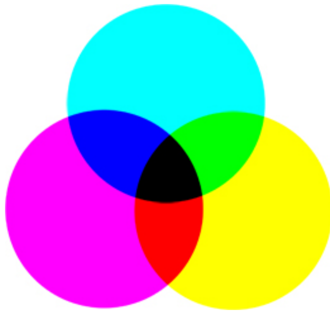

Figure 2.12: CMYK Model.[14]

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 Magenta and Red-Green produce Yellow. CMYK is a device-dependent space.

Defining Color Spaces

A color space is the set of colors originated by the specification of a mathematical model of primitives; it also allows the representation of reproducible colors on a given physical device. It relates the 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.

[14]"What is the difference (...)", Available at: `www.bit.ly/1OhuOlp`. Last accessed on October 17th, 2016.

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.

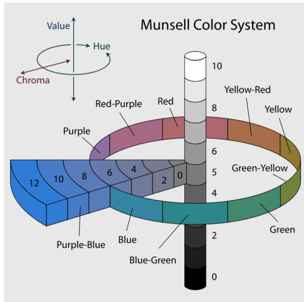

Figure 2.13: Munsell Color System.[15]

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.

CIE 1931 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 2.1.2, 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, CIE space allows the XZ plane to contain all possible chromaticities (a specification of a color, regardless of luminance) at a given Y luminance.

The CIE 1931 color diagram, as seen on the Figure 2.14, represents all the chromaticities visible to an average person, called the gamut of human vision., in particular several subsequent RGB color

[15]"Munsell Color System", Available at: `www.bit.ly/1mJsH3I`. Last accessed on October 17th, 2016.
[16]"CMYK Colour Model/Colour Space", Available at: `www.bit.ly/1TIo5pd`. Last accessed on October 17th, 2016.

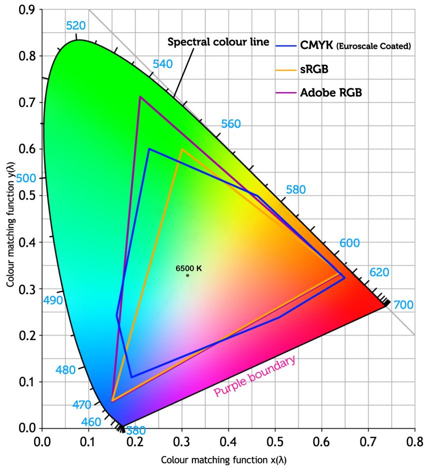

Figure 2.14: CIE Color Diagram, with CMYK, sRGB and AdobeRGB Color Gamuts depicted.[16]

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. It has a 3D shape, but the most recognized form is a 2D plane, with 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.
- 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 those 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: $x = 0.313, y = 0.329$. To contrast, **Illuminant A** (an incandescent tungsten light source) has coordinates: $x = 0.448, y = 0.407$, 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.

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 CMYK color model, as L*a*b* space contains both color gamuts.

There are some particularities related to this space: **i)** The values for the three variables are absolute, with a pre-defined range; **ii)** L* = 0 represents black and L* = 100 the brightest white; **iii)** As for the a* and b*, they will represent a neutral gray value at 0 value; **iv)** On the Red-Green Axis, represented by a*, the positive end a* being the Red component and the negative end the Green component; **v)** On the Blue-Yellow Axis, represented by b*, the positive end b* being the Yellow component and the negative end the Blue component; and finally, **vi)** 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.

Color Calibration

The accuracy of color is critical in design: the color you see on a monitor, sometimes, is not 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 colorimeters, which 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.

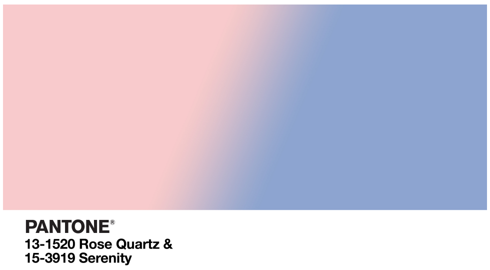

Figure 2.15: Pantone's Color of the Year.[18]

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 (as in Figure 2.15). 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[17]. PMS is used in a variety of industries, primarily offset printing.

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[18]:

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.

[17]"The Pantone Matching System®", Available at: `bit.ly/1ZdsYNU`. Last accessed on October 17th, 2016.
[18]"How To Comunicate Your Color.", Available at: `bit.ly/1OSrttr`. Last accessed on Jauary 8th, 2016.

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*.

Color Scales

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.

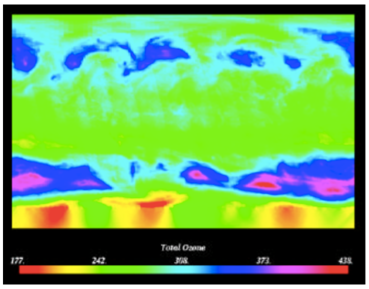

Figure 2.16: Spectrum Scale. [Rhe00]

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 2.16) 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[19]: 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 the observer), 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, since 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 2.17) is also very common, by combining gray scale and spectrum scale, it augments monotonically with luminance; it fluctuates from black, to red, orange to yellow and, in the end, to white. It happens to have more distinguishable perceptual steps and more contrast, than the gray scale.

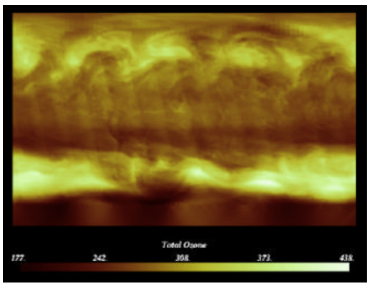

Figure 2.17: Heated-Object Scale. [Rhe00]

Rheingans defines **Hue-Other Scales** for two or more variables, as mapping variables to different color models, like hue, lightness or saturation. 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.

[19] "Dear NASA (...)", Available at: `www.blog.visual.ly/rainbow-color-scales/`. Last accessed on October 17th, 2016.

2.2 Related Work

Color plays an important role on how we perceive subjects and in the information we extract from them; it 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.

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 [GG14a].

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 complementary techniques try to recover.

In this section of the Background, we focus the attention on work previously developed in this research field. We start by analyzing the investigation conducted before, following it by an analysis of other user color studies which were performed in other domains of Infovis.

2.2.1 Color Blending Research and Techniques

Until the year 2014, some aspects remained to be studied. Gama and Gonçalves started their research [GG14c] 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 CMYK, fail to provide a color perception description, unlike HSV. This pitfall is amended by CIE-L*C*h*, by creating a perceptually uniform scale to lightness.

Data Visualization

A user-study was designed [GG14c] to assess the afore mentioned goals, 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 2.18. After, users were presented to colors blended into HSV, CMYK and CIE-L*C*h* and they had to pick the most natural transitions (bottom image of 2.18). 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.

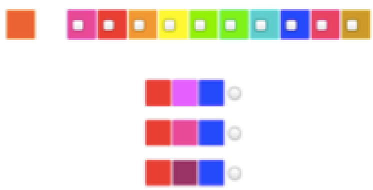

Figure 2.18: Example of Color Set. [GG14c]

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 CMYK 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 model).

The fact that CMYK 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 CMYK 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.

Perception of Relative Amounts of Color

Humans can perceive the original components that created a particular color: the final study performed by Gama and Gonçalves relating Color Blending Perception investigated precisely, the extent people can perceive relative amounts of color components in blended colors [GG14b]. 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. This has one major handicap: though reducing the cognitive load by associating colors to information, it may not show the expected accuracy if we do not understand human color perception.

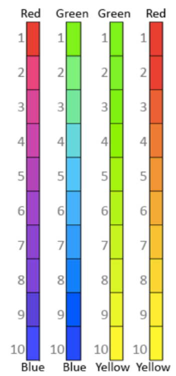

Figure 2.19: 10 Step Scales. [GG14b]

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 2.19. 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).

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.

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.

Other Research

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[20]. FiftyThree'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 color, gently swiping in circles to increase or decrease the mix.

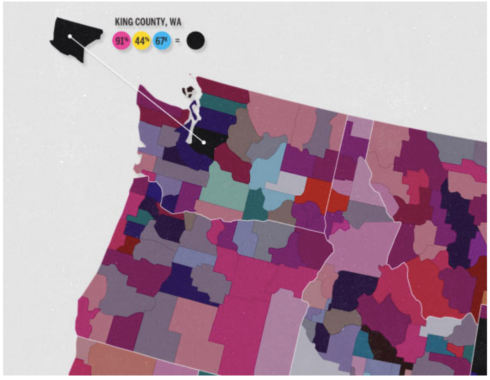

Figure 2.20: Bad Color Blending Usage.[25]

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 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[21]. However, the problem lies on the colors chosen to represent each variable: there were picked colors from the CMYK color model and they were mixed to convey information of three different variables at the same time; the problem in Figure 2.20 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.

Joshua Stevens presents[22] 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 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 2.21.

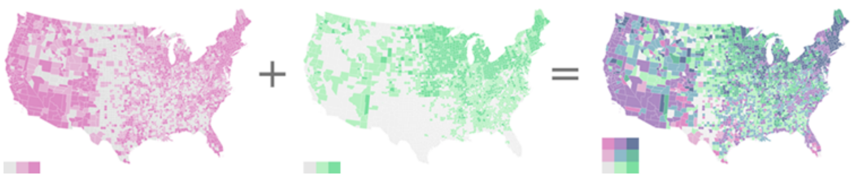

Figure 2.21: Choropleth Maps.[26]

[20] "The Magical Tech Behind Paper (...)". Available at: `www.bit.ly/1mIYpZK`. Last accessed on October 17th, 2016.
[21] "Reading, Writing and Earning Money". Available at: `www.bit.ly/1RwnibG`. Last accessed on October 17th, 2016.
[22] "Bivariate Choropleth Maps (...)". Available at: `www.bit.ly/17S3FaK`. Last accessed on October 17th, 2016.

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.

2.2.2 Color Blending Alternatives

Besides simple color blending techniques, researchers have been developing techniques in order to convey even more detailed and accurate information. Examples of these studies are: a technique of color weaving and a hue-preserver color blending technique, covered in this section.

Color Weaving

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 [UIM$^+$03]: 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.

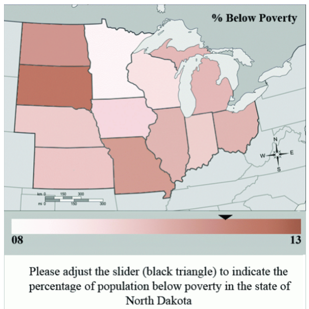

Figure 2.22: Example of a Map. [HSIHK06]

This technique was vastly studied by Hagh-Shenas *et al.* [HSIHK06]. These researchers created a set of 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 authors concluded that Color Blending and Color Weaving have a common problem: the background color and the surrounding color can change the appearance of a color. These studies also led to conclude that the technique of color weaving is substantially effective 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].

Perceptual transparency is the perception of an object being in front of another background object: the authors created an approach that is not subject to any type of physical constraint, but can be formulated as an algebraic model. They have reached a set of design criteria that lead to an equation which expresses the color addition in Hue-Preserving color blending: $C_{new} = C_1 \oplus C_2$

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 2.23.(c).

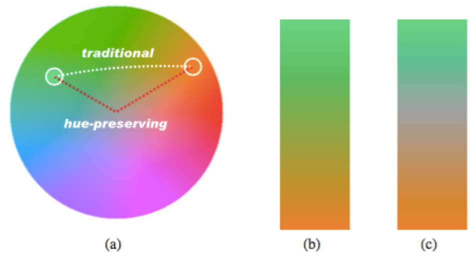

Figure 2.23: (a) Regular and Hue-preserving color blending. (b) Traditional alpha blending between teal and orange. (c) Hue-Preserving color blending ofteal and orange. [CWM09]

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: **A:** The blending from one input color C_1 towards the gray axis, keeping the hue of C_1, and **B:** 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 2.24), and this technique of blending colors is order-dependent, since blending colors in different blend orders can produced different results.

Figure 2.24: Example of a Regular Color Blending (left side of each image) *versus* Hue-Preserving Color Blending (right side of each image). [CWM09]

Other Investigation in Color Usage

Colormaps are commonly used in many domains in computer science, *e.g.*, computer graphics, visualization, computer vision and image processing. Particularly in visualizations, as they are able to improve the efficiency and effectiveness of data perception and therefore allow more insights into the data. Therefore, it is crucial for visualization designers and users to understand colormap generation techniques as well as the general rules for choosing appropriate colormaps for specific data. Zhou and Hansen [ZH16] provide a way to classify colormapping techniques into a taxonomy for readers to quickly identify the appropriate techniques they might use, classifying representative visualization techniques that explicitly discuss the use of colormaps. These authors gathered the investigation performed by other researchers in this paper. There are a set of standards for a good colormap, namely order (colors should have perceptual orders in a colormap), uniformity and representative distance in which perceived color distances should match actual differences between the data they represent; and boundaries where colors should not create false perceived boundaries in data. Additionaly, the authors classify colormap generation as: **procedural, user-study based, rule based** and **data-driven**, which shows that with a deeper understanding of colors and data, as well as the advent of more powerful computation, methods for colormap generation have evolved from procedurally designing a default colormap for all data, into more intelligent data-driven approaches as the state-of-the-art.

Stoffel, Janetzko and Mansmann introduced a new technique [SJM12] for visualizing proportions in categorical data; in particular, they combine bipolar colormaps with an adapted double-rendering of polygons to simultaneously visually represent the first two categories and the spatial location; as the example given in their paper, this enables the recognition of close election results as well as clear majorities, or other similar subjects. Representing data variables in a map makes the choice of visual variables more challenging, as the most important variable, namely position, is already occupied representing the geographic location: therefore, when showing values of a categorical data set, it stands to reason using color hue to represent the different categories (in the particular case of this example, each party). The difference in this technique resides in reusing the visual variable shape by placing a shrunk polygon of the specific shape on top of the original polygon, to express the distance to the second ranked category: if the distance between both polygons is very large, then the winner is far ahead of the second one, and the inner polygon will be very small, and vice versa. While attributing a color to categories, the outer polygon is filled in the color of the winning party, and a gradient fill is applied from the color of the second party (inner) to the color of the winner (outer). However, there is one issue addressed here, namely the visibility of the first ranked category in cases of a very tight result: in this case the outer polygon would diminish and could not be visible at all; also, this techniwue cannot handle different sized polygons very well as the visual salience of large polygons will always exceed the salience of small polygons. Figure 2.25 exemplifies a map for Germany's 2009 Elections, showing the results crossed for all parties.

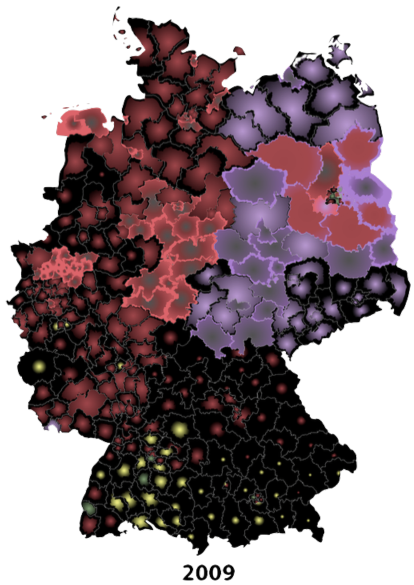

Figure 2.25: Stoffel's Technique to Visualize Proportions with Hues. [SJM12]

2.3 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 [GG14c], 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 CMYK 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.

On the other hand, Gama and Gonçalves tested how the users perceive relative amounts of color [GG14b], 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**, by Hagh-Shenas [HSIHK06]. 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. It was also studied by Stoffel and felow researchers [SJM12] a Technique to present more than one variable at time, in a map, using hues: it attributed a color to each shape of the map and placed a shrunk polygon of the specific shape on top of the original polygon, to express the distance to the second ranked category. Then, the polygons were colored according to a pre-defined mapping of colors and categories: the outer polygon is filled with the color of the winning category, and a gradient fill is applied from the color of the second category (inner) to the color of the winner (outer).

Considering these conclusions drafted from both the theoretical background and research related work, we can divide the possible questions which remain unaswered as follows:

- **Questions raised Before**
  - Will perceived colors correspond to a particular fixed angular value, in the color wheel?
  - Which is the best formula to blend colors, in each color model? Is it linear interpolation or another?
  - In the case in which 3 colors are blended, do observers realize all colors at the same time or do they decompose the mixture, firstly in a mixture of two colors and then a blending of a third color?
  - What is the best way to present color, without influencing color perception?
  - Does the user, in fact, understands which colors are involved in a mixing?
- **Perception Questions**
  - Does the order in which colors are mixed, influence mental mixing models? Are there common patterns among mixing orders?
  - Do shapes and proximity, influence how color is perceived?
  - Until which extent does background influence the perception of a subject, in particular a blended color?
  - If color parameters like Saturation, Value or Luminance change in a blending, does it modify color blending perception?
- **Information Visualization Questions**
  - Do continuous scales yield better results than discrete color scales?
  - What is the influence of nominal color scales in perception?
  - What are the results if no color scale is presented to guide the user?

- **Cultural Questions**
  - Does the gender really influences how the color is perceived? Is it possible to observe a significant gap between male and female answers?
  - Is it possible to observe significant differences in observation, depending on user's cultural background?

Although we have rised all these questions which do not have met its answer, only a portion of them will meet their answers, since this is Master Thesis Research Problem. However, there is a set of these questions which was considered crucial and, consequently, had more priority above others: it was this set which was the focus of our studies. We performed **one user study** and, in the following sections, it is covered the entire description of the solution developed for this color study, the conditions in which the study is ideally performed and analyze the results collected from it. In the end, we will perform a discussion of results and deduce some possible implications for the Information Visualization research area.

Chapter 3

BlendMe! - The User Study

This chapter of the document concerns the design and implementation decisions fulfilled when developing the supporting platform of our user color study. For the sake of simplification when describing and talking about this platform, we have called it *BlendMe!*, since its purpose is to support the collecting and analysis of data from color blendings!

We are going to state the objectives for this user study, concretely defining the questions which we want to have answers in the end of the study; then, we will discuss how the *BlendMe!* was implemented, justifying the decisions taken in each phase of the study. To end this section, we will define evaluation criteria which is going to be important for the data cleaning and processing phase of the research.

3.1 Objectives

As seen before, there is a myriad of questions about the usage of color blendings when conveying information, which remained unanswered. However, only a set of questions is answered in our research, since it is not possible to reach answers to all questions. Therefore, the goals which we have picked for this User Study were to understand if color blendings can be detected by the users, is it easier for users to estimate the pair of colors that resulted in a particular given blend, or reciprocally, to estimate which blend will result from a given pair of colors, to detect if the users follow some kind of mental convention and organize the color when conveying the answers, and formulate possible implications of color blending usage, in Information Visualization field of research.

Additionally, it is relevant to understand which color model stands as the best to mix colors which are, from a perceptual point of view, more similar to the users expectation. We have planned to develop this study in two different strands: in a **Laboratory Environment**, which will allow us to calibrate and perfectly control the entire study conditions, and in an **Online Environment**, which will allow us to disseminate our study to a larger set of users, even without controlling the calibration of the testing environment, but that may be useful to corroborate the laboratory results with a larger user sample.

The questions which we think define our research goals, for this study, are:

- **Q1:** Which Color Model best meets the users' expectations, when blending two colors?
- **Q2:** Do users specify the Blending-basis following some order, when users are indicating possible color mixtures' results?
- **Q3:** Are there evidences from differences across demographic groups, such as the age or gender?

Along the result analysis, each question will meet its answers. These questions will be explored in multiple threads, such as: 1. **Analyzing the distances of each answer pair to the ideal answers**

of each color model, verifying which color models had the best and the worst values yielded by the descriptive statistic analysis, 2. **Evaluate the results from blendings when the basis is given to the user, against when the result of the blending is given**, 3. **Verify if the color models which have the best and worst results are subtractive or addictive**, 4. **Analyze the ease of blending colors**, or if 5. **There is substantially different results among genders, or different age groups**.

To meet these study requirements, we drafted our study into three different phases: a **User Profiling Phase**, a **Calibration Phase**, a **Color Deficiency Test Phase** and finally, the **Core Phase**. In the following section, we detail each of these study phases.

3.2 Designing the *BlendMe!*

Since we aim to *study to what extent can color blending techniques be used to efficiently and effectively convey information*, it is important learn from previous results, testing out not only the validity of them but also some missed opportunities.

One of the points discussed in section 2.3 was the amount of users who performed the study of Gama and Gonçalves [GG14c, GG14b]: it was large enough for their questions. However, considering the results we aim to achieve with this study, a considerably larger sample of users is the ideal: besides conducting the study in a laboratory environment, it is mandatory to expand the sample size by performing user studies with online users, taking advantage of the cultural diversity that may arise.

Therefore, we intended to develop a user study which could support the laboratory controlled environment, while at the same time supporting the collection of metrics and data from the online users: this is an important consideration, since the workload when analyzing the results would be dramatically reduced because the data is condensed and gathered in the same fashion, and data would be more comparable. As referred, the user study was divided onto four different stages: the **user profiling**, **calibration testing**, **color deficiency testing** and, finally, the **principal part of the study** where the core information was collected from the users. Each of these phases will be addressed later in this section.

When brainstorming the ideas for this study, we started with the intention of testing both the blending of two colors and three colors; we decided that the colors which would be blended were Red (**R**), Green (**G**), Blue (**B**), Cyan (**C**), Magenta (**M**) and Yellow (**Y**), since they represent each primitive of the most commonly known Color Models, RGB (Additive Color Model) and CMYK (Subtractive Color Model).

The color models we intended to study: the color models were **HSV, RGB, CMYK, CIE-L*a*b*** and **CIE-L*C*h***. These color models were picked according to previous studies conducted by Gama and Gonçalves, which have concluded that HSV and CIE-L*C*h* were the models which generated better results [GG14c, GG14b]; the RGB and CMYK were obvious additions, since they are represented by their primitives and we wanted to compare the users' expectations with two representative different color model types (additive and subtractive). Lastly, the inclusion of CIE-L*a*b* was due to the fact that it is the color model which represents the entire range of human perceivable colors.

Then, we produced a wide spreadsheet of possible blendings of these colors, according to these color models, **mixed in pairs of two colors** and **triples of three colors, without opposed colors in HSV angle**: this last restriction derives from the fact that, since the HSV Color Model provides angular values for hues, there are colors from the set we have chosen that have opposed angles (R-C, G-M and B-Y); therefore, when interpolating the angular values for these colors, the resulting color could be obtained on another two opposed resulting angles. If we had added these color pairs to blendings with three colors, color blendings with one of these three pairs would provide, at least, two possible outputs. Then, we have only produced blendings of three colors which did not contain any of these three pairs, in order to simplify its future analysis.

This generated the total amount of 183 Color Blendings, being 78 from blendings of two colors and 105 from blendings of three colors. **There are 15 possible mixtures of two colors**, when combining the previous defined colors: R-G, R-B, G-B, R-C, R-M, R-Y, C-M, M-Y, G-C, G-M, G-Y, B-C, B-M, B-Y and C-Y; on the other hand, there are 21 possible color mixtures of three colors without opposed colors in the HSV hue circle: R-G-B, R-B-G, B-G-R, R-M-B, R-B-M, B-M-R, C-G-B, C-B-G, B-G-C, C-M-Y, C-Y-M, Y-M-C, C-M-B, C-B-M, B-M-C, C-G-Y, C-Y-G, Y-G-C, R-M-Y, R-Y-M and Y-M-R. Figure 3.1 shows an excerpt of the table produced: it depicts the results, for each color pair, blended according to the five color models chosen.

Two Color Blends	HTML				
	HSV	CIE-L*C*h*	CMYK	RGB	CIE-L*a*b*
R-G	#FFFF00	#D7A700	#808000	#808000	#c9ab00
R-B	#FF00FF	#FB0080	#800080	#800080	#ca0088
G-B	#00FFFF	#00A5FF	#008080	#008080	#7d93a6
R-C	#80FF00	#91c01d	#808080	#808080	#dda581
	#7f00ff				
R-M	#FF0080	#FF0080	#FF0080	#FF0080	#ff0087
R-Y	#FF8000	#FF9F00	#FF8000	#FF8000	#ffa100
C-M	#0000FF	#00caff	#8080FF	#8080FF	#c6aeff
M-Y	#FF0000	#FF6755	#FF8080	#FF8080	#ffa6a6
G-C	#00FF80	#00ffb7	#00FF80	#00FF80	#46ff9c
G-M	#0080FF	#FF6F00	#808080	#808080	#c9b2a2
	#ff8000				
G-Y	#80FF00	#B1FF00	#80FF00	#80FF00	#aeff00
B-C	#0080FF	#00acff	#0080FF	#0080FF	#5792ff
B-M	#8000FF	#B000FF	#8000FF	#8000FF	#ab00ff
B-Y	#00FF80	#FF0050	#808080	#808080	#ca8aaa
	#ff007f				
C-Y	#00FF00	#6effa3	#80FF80	#80FF80	#c4ff9e

15 Blends

Figure 3.1: Excerpt of Table containing the pre-calculated Color Blends.

For the sake of simplicity, we have decided to drop the idea of testing the blendings of three colors, since the blendings of two colors already produce a generous amount of possible questions, and Gama and Gonçalves already concluded that blendings of three colors do not provide satisfactory results [GG14c]. This table was converted to Comma Separate Values (CSV) file, which will be useful in the Core Phase of the study, which will be explained later.

Question ID	Given the Result, Asked for Basis	Question ID	Given the Basis, Asked for Result	
	Given Color		Given Colors	
1	#FFFF00	18	#FF0000	#00FF00
2	#FF00FF	19	#FF0000	#0000FF
3	#80FF00	20	#00FF00	#0000FF
4	#7F00FF	21	#FF0000	#00FFFF
5	#FF0080	22	#FF0000	#FF00FF
6	#FF8000	23	#FF0000	#FFFF00
7	#0000FF	24	#00FFFF	#FF00FF
8	#FF0000	25	#FF00FF	#FFFF00
9	#00FF80	26	#00FF00	#00FFFF
10	#0080FF	27	#00FF00	#FF00FF
11	#FF8000	28	#00FF00	#FFFF00
12	#80FF00	29	#0000FF	#00FFFF
13	#0080FF	30	#0000FF	#FF00FF
14	#8000FF	31	#0000FF	#FFFF00
15	#00FF80	32	#00FFFF	#FFFF00
16	#FF007F			
17	#00FF00			

Table 3.1: Two types of questions asked about Color Blendings.

Since we wanted to **test if it is better to give the result already mixed, or indicate the blending-basis and the users create the color mixture**, we developed a set of 32 questions to present to the user: 17 of them are of the type **presenting the resulting color, and ask for the blending-basis**, and 15 of them are of type **given the blending-basis, ask for the blending-result**. The entire set of questions is mapped in Table 3.1: as seen, for each color-pair, we have interpolated it for each of the five selected color models. Concerning the questions from 1 to 17, we present the results of blending the aforementioned colors according to the HSV Color Model: there is no concept of wrong or right answers, but instead a referenced answer-pair for each blending result. Thus, we can compare the answer pair given by the users with each reference pair, measuring the euclidean distance between each pair. For example, when presenting Question 1 to users, we show a **Yellow color and expect that the answer-pair given by them is composed of Red and Green**; then, the answer-pair is interpolated in each color model and the result is compared with the one according to each color model. Regarding questions from 18 to 32, they present each reference-pair (composed of two color primitives) and the users are expected to indicate a result, from the entire set of possible results depicted in Figure 3.1.

There is a particularity among these questions: questions 2 and 3 present two different colors (#FF00FF - #80FF00) but, in fact, they will be compared with the same reference pair. This is the result of blending to opposite colors (Red-Blue) which, as referred before, results into two possible results; by presenting both results, we intend to understand to which color the users tend to. This particularity occurs with questions 10 and 11, and 15 and 16 (#0080FF - #FF8000, #00FF80 - #FF007F, respectively), which will be compared with reference pairs Green-Magenta and Blue-Yellow, correspondingly.

This user study was entirely developed used web-development libraries (*e.g.* Bootstrap), technologies (*e.g.* HTML5, Javascript and CSS) and relational databases (PostgreSQL): the users are uniquely identified by a primary key (PK) which corresponds to its user ID generated by *uniqid()* function from PHP, based on the user's timestamp, that every table from the database uses to unequivocally identify it. An entity-relationship model maps all the information related to a given a user which will be stored for further analysis; this ER Model is present on Figure 3.2.

Being this an online published user study and known that we wanted to converge the inputs from all users in the same platform, we have executed this study in a web browser: we have executed the majority of tests using Google Chrome and a few using Safari.

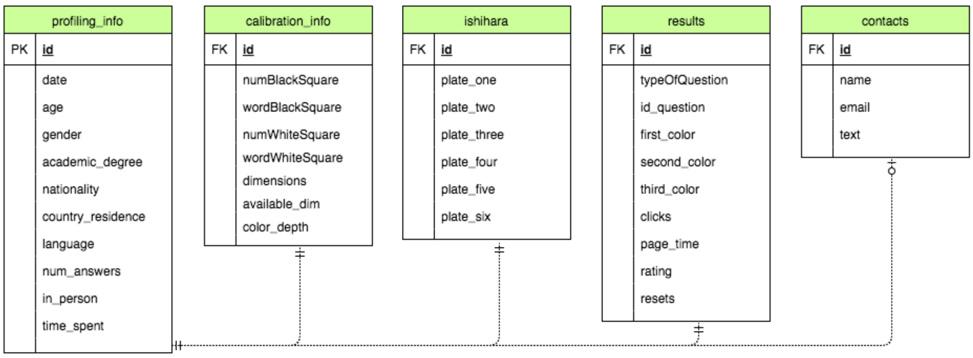

Figure 3.2: Entity-Relationship Model representing the User Study information.

3.2.1 User Profiling Phase

In the **Profiling Phase**, questions were asked about the Age, Gender, Academic Degree, Nationality and Country of Residence: these questions helped us conceiving user profiles with key indicators about cultural background and gender relation to results of each test. We have drafted a wireframe version of this test phase, which is present in Figure 3.3. This is a straight-forward phase, in which the users are asked to indicate some demographic information. All of these information are stored in a relational database's table called *calibration_info*, which will be entry point of the database. We had to include the Other gender type, since it was mandatory by Reddit to publish it online. The nationalities, academic degrees, countries of residence and native languages were all standard JSON files which contained each set of options.

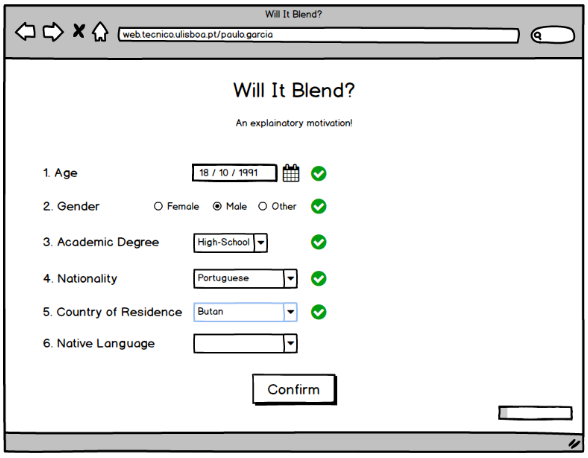

Figure 3.3: Mock-up of Color Study's User Profiling Phase.

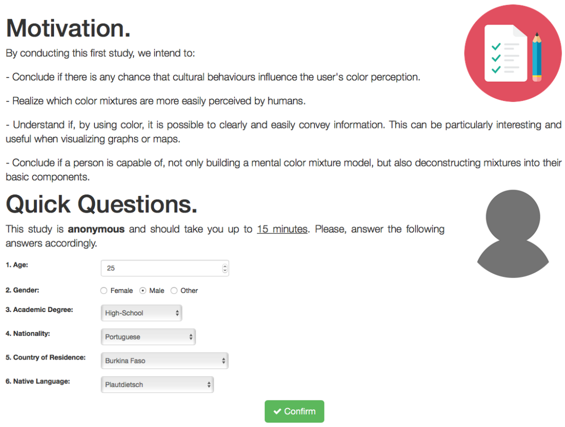

Figure 3.4: Screenshot of Color Study's USer Profiling Phase.

Figure 3.4 presents a snipping of the interface implemented for this user study phase: be aware that this screenshot has been shrunk down to a proper scale for this document, so the proportions of the interface are not the ones presented to the user.

When this phase was concluded, the user was guided to another stage of the study, to perform the **Calibration Phase**, where he was asked to analyze a set of images and answer a pair of questions.

3.2.2 Testing Calibration Phase

Performing online tests - specially when trying to obtain precise values about color - carries obvious problems of how it is guaranteed that the results which may appear are, in fact, compliant with certain patterns of quality, specially color and monitor calibration patterns; to overcome this problem, the ideal solution would be to develop a system capable of acquiring information about the user's monitor calibration, *e.g.* Brightness, Contrast, RGB Color Balance, Gamma or Saturation, as a pre-step of the study and apply an appropriate calibration when rendering the study's main page.

Figure 3.5: Calibration image: Black-Level Measure.

Figure 3.6: Calibration image: White-Level Measure.

Since we have not found a way to tackle this solution so far, we developed another solution for remote controlling the calibration on the online environment: to present two similar calibration images, one presenting a set of shaded squares ranging from grey to black shades against a black background, and another presenting instead white squares against a white background. All of the squares presented a red number in its corner and it was accompanied by a random word, shaded in same color as the square it follows: the user's task was to provide us the number (and word) from the last square which he could easily see. This information provide us input about the white-level and black-level of the screen, which are nothing more than the **Contrast** and **Brightness**, respectively, of the display. This test is inspired in PLUGE (stands for **P**icture **L**ine-**U**p **G**eneration **E**quipment) Patterns, which present consecutive bars shaded between black and white, used to calibrate the black-level from a video monitor. These calibrations images were created by us, using Adobe's Photoshop, and are presented in Figures 3.5 and 3.6. In the end, we have to analyze the answers to verify if they are compliant with a certain pattern of calibration acceptability, determining if the answers of a certain user can be considered true and not misleading.

Regarding the laboratory environment, we conducted the users tests in a LCD monitor, under a fixed light source; the monitor was calibrated using a Spyder[1] Colorimeter which will consider the existing light in the environment and adjust the color of each pixel to a standard. This colorimeter will produce an *.icc* **color profile which will be important for the Core Test Phase**.

We have also included in this interface the protocol to be followed when calibrating the screen, which is covered in Section 4.1. Figures 3.7 and 3.8 represent the wireframe version of the screen, which only contained one image as example, and the final version which was presented; however, the second one only shows the part where it was tested the black-level, since the interface for this phase is quite extensive.

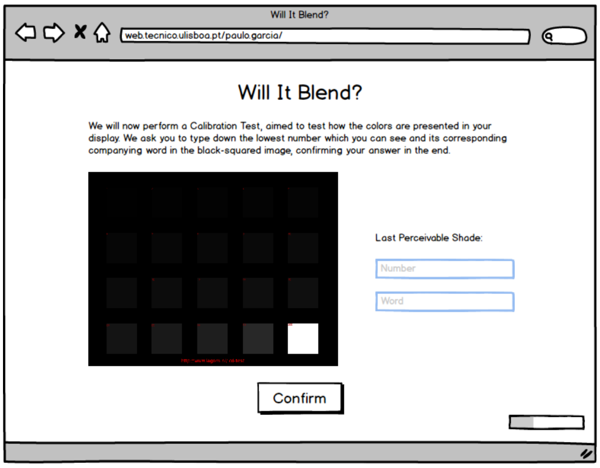

Figure 3.7: Mock-up of Color Study's Calibration Testing Phase.

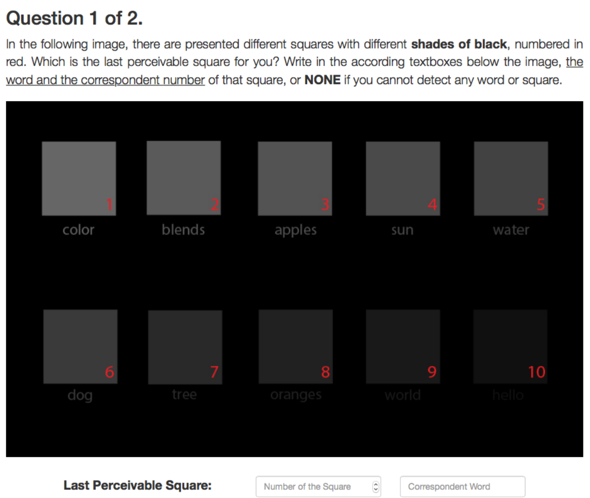

Figure 3.8: Screenshot of Color Study's Calibration Testing Phase.

When this phase was concluded, the users were guided to another stage of the study, to perform the **Color Deficiency Test Phase**, where they were asked to analyze a set colored plates and answer with its number.

3.2.3 Testing Color Vision Deficiencies Phase

The Color Deficiency Test was comprised of a set of six plates, which were able to detect which type of color vision deficiencies the user would eventually have. They could be interpreted in different ways, depending on Deficiency: this color deficiency test in commonly known as the Ishihara Test, which has a validated [dAK92] short form that rearranges the order in which the plates are presented. We have only chosen plates which detect color vision deficiencies in the Red-Green field, since it is the most common deficiency. This test was explored in the Theoretical Background (Section 2.1.2) of this Master Thesis. We have chosen the following plates:

[1]"Spyder - Datacolor Imaging Solutions", Available at: `http://spyder.datacolor.com`. Last accessed on October 17th, 2016.

- Plate #1 - We have chosen [dAK92] the plate ($ID = 1$) which presents the number **12**. This is an Instruction and Demonstration plate, since every user should be capable of viewing the number and it is intended to demonstrate how to interpret the plate numbers.

- Plate #2 - This plate ($ID = 4$) presents the number **29**. This a plate from the Transformation group, presenting the number **29** for regular users which do not have any color vision deficiency, and the number **70** to users which have a color vision deficiency in the Red-Green field.

- Plate #3 - This plate is a confirmation from the result of the previous one. This plate ($ID = 9$) presents the number **74**, also a Transformation one, presenting **74** to regular users and **21** to users which have a color vision deficiency in the Red-Green field.

- Plate #4 - This plate ($ID = 13$) presents the number **45**. This is a Discrimination plate, since all the regular users see the number **45**, and the ones which color vision deficiencies are supposed to see a blob.

- Plate #5 - This plate ($ID = 22$) presents the number **26**. Both this plate and number #6 are Classification plates: the regular users see the normal **26** number, the ones which have Deuteranopia see only the number **2** and the ones which have Protanopia see only the number **6**.

- Plate #6 - Finally, this plate ($ID = 24$) presents the number **35**. Similarly to before, this plate is a confirmation of plate #5: the regular users see the normal **35** number, the ones which have Deuteranopia see only the number **3** and the ones which have Protanopia see only the number **5**.

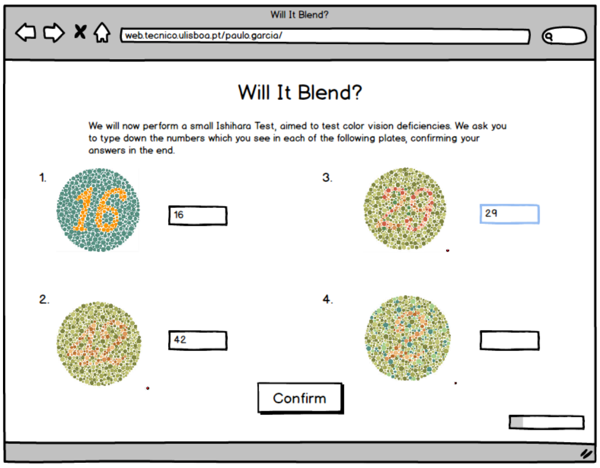

Figure 3.9: Mock-up of Color Study's Color Deficiencies Test Phase.

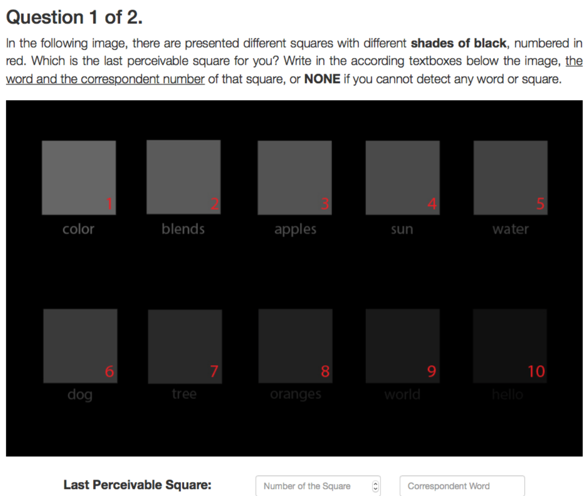

Figure 3.10: Screenshot of Color Study's Calibration Testing Phase.

In this test phase, the users only had to interpret the Ishihara plates and indicate the value which they saw on each of the six plates; these results would be analyzed later, indicating which users were color vision deficient, therefore leading to a separate analysis. Figures 3.9 and 3.10 show the evolution between the original mock-up and the implementation of the test phase, once again depicting only a part of the interface since it is an extensive one. When this phase was finished with success and answers were submitted, the users could proceed to the **Core Test Phase** of the study, where they would be asked about the pre-calculated color blendings referred on 3.2.

3.2.4 Core Test Phase

The last phase is the principal part of the study, which will evaluate the **Blending of Two Colors**. It was presented the set of color combinations created from the principal color models' primaries referred before and these color blendings are represent in Table 3.1.

In this test phase, we have composed an interface with the description of the task to fulfill and presented a small set of objects which would be used and interacted with to provide the colors to the user, and receive his input values. Perhaps, the way color is presented is the most relevant detail: since we wanted to provide a tool which would be capable of displaying without being influenced by its surrounding of even by the proximity of other colors, the colors were presented in rounded shapes, accompanied by what we call ***color sliders*** whenever it was needed input colors from the user. With this, only the necessary colors are displayed on the circles as the users wish and there is no interference of undesired colors, allowing us to eliminate the influence of them. The sliders will alternately present a discrete or continuous color scale underneath, according to the type of question which is being presented to the users.

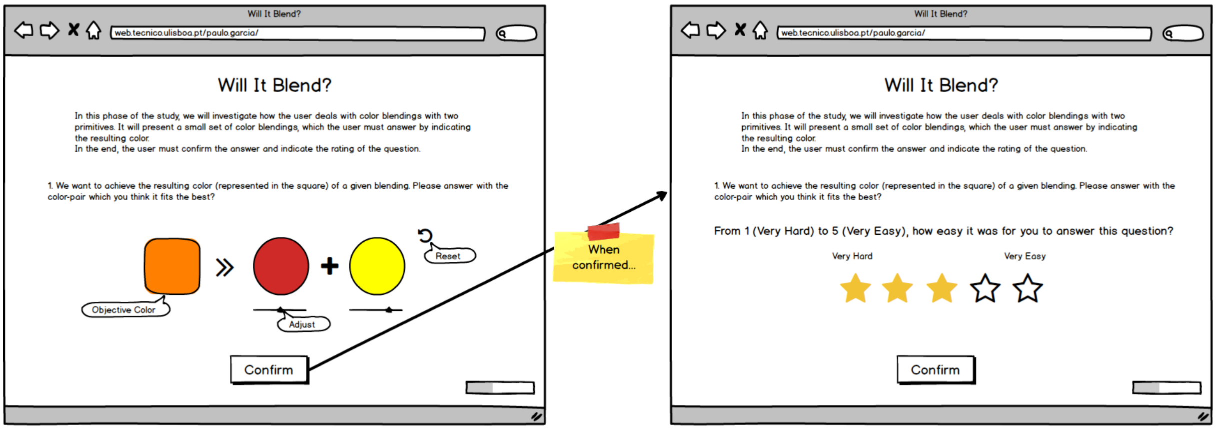

Figure 3.11: Mock-up of Color Study's Core Test Phase: presenting the result and asking the blending-basis.

Since there are two possible types of questions, we have wireframed two screens: in the first one, we display a shape filled with the objective color of the blending and two empty shapes which the users should fill with the colors that they think it corresponds the best to their expectations. These shapes start filled with an empty color (or white) so the users are not influenced by previously used colors, when answering to another question. There is no particular reason for the chosen shapes are circles, since **we are not studying the best visualizations to convey information, when using color blending techniques**. These shapes presented against a white background so it **does not influence color perception**, equally spaced between each other, being followed by a small set of arithmetic operands which leads the users to realize they have to add a pair of colors. This screen is depicted in the left side of Figure 3.11.

The other screen presents exactly the same number of circle shapes (three), but one less color slider since this screen is designed to attend questions in which the blending-basis is already given and the users have to blend them, indicating only one answer. These two screens appear, alternately, in a random fashion so the users do not create any kind of habit or routine when blending the colors from the 32 questions. This screen is depicted in Figure 3.12.

The most interesting fact of this test phase is how the color slider works: we chose the HSV Color Model to represent the colors to show, since the **HSV Color Model has the best compromise when presenting colors in information visualization** because of its primitives (Hue, Saturation and Value) which allows to manipulate colors in a better way. However, **we have chosen to only modify the Hue**

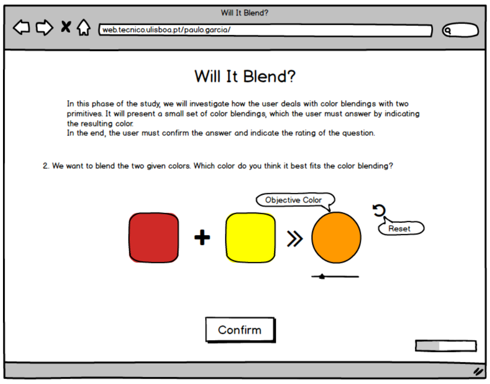

Figure 3.12: Mock-up of Color Study's Core Test Phase: presenting the blending-basis and asking the resulting color.

value and leave the Saturation and Value on its maximum value: this way, we could ensure that we could present the entire range of colors at its full saturation and value, also simplifying the gathering of values from the users. Therefore, the color slider yields a value within the range of $[0; 360]$ degrees which corresponds to an angle in the Hue circle of the HSV Color Model.

The color slider has another particularity: the scale of values, though representing continuous angle values, does not presents the values ordered from 0 to 360. Instead, **fixed intervals of values are mixed within each other**, so the users do not formulate any mental organization in the moment and do not demonstrate any previous conception or mindset (*e.g.* the organization of colors according to the color spectrum). The colors were arranged in the following order: Red-Yellow ($[0^o; 60^o]$), Blue-Greenish-Blue ($[240^o; 150^o]$), Magenta-Blue ($[300^o; 240^o]$), Greenish-Blue-Yellow ($[150^o; 60^o]$) and, lastly, Magenta-Red ($[300^o; 360^o]$). If these intervals were disposed in its normal order, the order would be seamlessly perceived by the user: this way, **the users always have to search for the color they wants to see depicted**. For the questions which the users have to give only one answer (the resulting color from the blend), the color slider already yields a defined set of pre-calculated colors (the ones present in the referred spreadsheet, on section 3.2), and the users hand-pick the best-fitting solution from that set.

However, even the colors represented in the shapes and the ones present in the pre-calculated answers have a particularity, in the laboratory environment: these pre-calculated values are, with the help of a *Matlab* script, going to be **converted to adapted color values, according to the .icc color profile file generated by the Spyder Colorimeter**. This way, we guarantee that no matter if the laboratory environmental conditions change, the colors will always be presented equally to every user. **This script processes each possible result for every color pair, in every color model**, converts it to a normalized CIE-XYZ value and in the end, to an hexadecimal color code to be printed on the shapes of the interface, when time comes for the laboratory user to choose a color from the color slider. This process was realized before each user session.

After the users indicated and confirms their answer, **they were presented a satisfaction question with a 5-point Likert Scale** to double-check the easiness of each mixture. The question asked was **"How Easy it was for you to Identify the Mixture?"**; the users had to select the equivalent rating in a five-star system. If the users were not happy with its response, it was provided a "Reset Mixture" button to clean all parameters. All of these details are showed in Figure 3.13, which shows the resulting interface for the type of questions in which the result was given and the blending-basis was asked.

In the end, the users were thanked for the time they spent performing the test and it was provided a Contact Form, so the users could leave their feedback or demonstrate the interest (or not) for this subject. All of the data was being stored in the table *results*: a portion of example from the type of data gathered is present on Table 3.2.

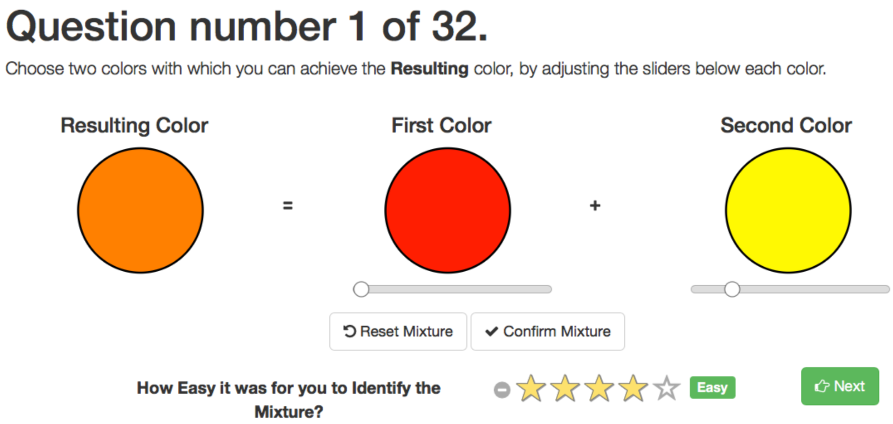

Figure 3.13: Screenshot of Color Study's Core Test Phase: presenting the resulting color and asking the blending-basis.

User ID	Type	First Color	Second Color	Third Color	Drags	Time	Rating	Resets	Question ID
5710cca334d60	objTwoColors	#0080FF	hsl(58.69565217391305,1,0.50)	hsl(98.15217391304348,1,0.50)	992	117	4	2	10
5745c1c07cc0c	objTwoColors	#8000FF	hsl(300,1,0.50)	hsl(324.13043478260875,1,0.50)	645	55	2	1	14
5745350dc1e22	objTwoColors	#0080FF	hsl(226.30434782608697,1,0.50)	NONE	115	11	5	1	10
57451c3b38192	objTwoColors	#00FF80	NONE	hsl(150,1,0.50)	462	39	5	1	15
574511e99b6d9	objTwoColors	#0080FF	hsl(15.652173913043478,1,0.50)	hsl(316.30434782608694,1,0.50)	442	40,	1	1	10
57427cf6bad0c	twoColorsObj	#00FFFF	#FFFF00	#46FF9C	6	14	3	1	32
5740bda9be3dc	objTwoColors	#FF7200	hsl(9.130434782608695,1,0.50)	hsl(50.21739130434783,1,0.50)	45	22	5	1	11
573c783748e8b	twoColorsObj	#00FFFF	#CBFF00	#00FF6B	44	25	3	1	32

Table 3.2: Excerpt of Results Table, with raw data.

3.3 Evaluation Criteria

For a user and its responses to be considered as valid, they have to be evaluated against the following set of rules:

1. For Profiling and Ishihara Test Phases, it is considered as valid the values which are very close from the expected one, since there might have been, inadvertently, a slight drift when using the *HTML5* input type "Number" objects.

2. For Profiling and Ishihara Test Phases, it is considered as valid the values which are extremely apart from the expected one, if: **A:** it is an extraordinary situation, for just one plate and no other, and **B:** if it happens in more than one plate, but in the ones which have a presented value, it could be related to an evaluation criteria for that plate.

3. A user and its answers are considered **invalid** if the results for the majority of plates have extreme values (*e.g.* 1 or 99), and the number of answers given is irrelevant.

4. For Plate #1, it is considered valid all the users which have answered with the number **12**, since this is an Instruction/Demonstration plate, being interpreted as a control flag, indicating if the user was aware of his task.

These criteria will be important in the following section, in which we clean the data gathered along the user color study, process, analyze and infer conclusions. Besides, these criteria, it should be followed the ones defined in Section 3.2.3 which concern the analysis of color vision deficient users. It will help us defining which users provide useful inputs, and how to separate them among datasets.

Chapter 4

Analyzing Color Mixing Perception

In this Section, we are going to dive into the results obtained from the user study described on chapter number 3. On the first Section, we will clearly explain the test protocol which was followed by the users in the laboratory environment to correctly execute the study; this Section will be followed, not only by the description of how the gathered data was treated and cleaned (Section 4.2), but also the transformation of this data using *Matlab* processing tools, in order to prepare it for the statistical scrutiny (Section 4.3). Hereafter, conclusions will be drawn from the study at Section 4.4, when trying to find answers to the questions/objectives raised before.

The final Section of this chapter will be dedicated to summarize the results and infer important conclusions, implications and guidelines which could be relevant for the InfoVis field of research.

4.1 Protocol

The existence of a test protocol, when performing a User Study is mandatory: without it, the test may not follow a strictly previously defined standard. As written before, this user study was conducted two-pronged: in a laboratory environment and *via* online dissemination channels.

4.1.1 Laboratory Environment

The users were given always the same briefing when they arrived at the user study test site: it was explained the motivation behind the master thesis, the goals which were expected for this phase of the study and what was expected for them to execute. The most important information which was told was that ”there are no pre-defined correct and wrong answers to each question, this test was designed to test the general color mixing capabilities of the majority of the users”. Besides this information, the user study was self-contained, in the sense that every other relevant information and instruction was in the interface, adapted for each test phase, so it was not given any physical artifacts giving instructions. The instructions were available on two languages, depending on the choice of the user: Portuguese and English.

Before each session of the laboratory environment test-run, a Datacolor® Spyder 5 Elite Color Calibrator was USB-connected to the computer and, using the software which is shipped along with it, the computer's LCD display was fully calibrated (the software offers the option of recalibrating, the option of checking the calibration and also, the option of fully calibrating the display) by testing the pixel emission when emitting a particular set of colors; the LCD display was fully calibrated before every test.

The tests were conducted sixteen times in Rede Novas Licenciaturas (RNL) at Instituto Superior Técnico (IST), and twelve times in other locations with similar conditions: this is due to constraints in finding users, so the test site needed to have a (limited) mobility feature. However, the conditions remained the same concerning the illumination, the position of the user and the computer used: a Macbook Air 13' (Mid-2013) was prepared underneath a fixed incandescent light-source (but slightly deviated from it, to minimize light reflections on screen), the user would sit in front of the laptop, in an almost silent environment. Ideal conditions of this test would be such that the user could be sitting alone in a completely silent room, his head would be always at the same distance from the screen, resting is chin in a head-rest and the LCD display's inclination would be perfectly adjusted to the user's eyes.

4.1.2 Online Environment

Performing the study online, as easily predictable, develops some characteristics which cannot be completely controlled. For the sake of calibration, the user was asked to to perform a set of six calibration easy steps before starting the test, so the online user's screen would be, somehow, in a standardized calibration fashion. The calibration steps which were asked are:

1. If possible, adjust your room lights for a comfortable usage of your device.
2. Avoid reflections on your screen, by diverting the screen from direct sources of light. This step is important, since light reflections can affect visualization of images.
3. To adjust the **Black Point** of your screen, define the Contrast and Brightness of your screen to their maximum.
4. After Step 3, gradually reduce **Brightness** value of your screen, in order to correctly distinguish the squares of each image below [calibration squares images].
5. If possible, define the **Color Temperature** of your screen to 6500 Kelvin Degrees.

The ideal conditions of this test would be such that we could control and manipulate the color calibration of online user's LCD display, using a software piece which would acquire important information from the screen configuration, *e.g.* resolution, white-point, black-point, brightness, among others, digest the values and present the questions from the Core Phase in a completely controlled and calibrated window. Further investigation could focus in developing this system.

The users were asked to fill in a profiling questionnaire (as seen of Section 3.2.1), as well as to respond to a calibration form (Section 3.2.2). A validated simplified 6-plate Ishihara color blindness test [dAK92] is, then performed (Section 3.2.3), before proceeding onto the 32 questions test-phase, in which the user is asked to slide one (or two) circular object(s) placed on top of a bar, to indicate a(the) color(s) which he thought were the correct mixture answers. In the end, the user could leave feedback, by sending a message which would be stored to be analyzed.

The instructions which were presented in each page can be consulted in Appendix A.

4.1.3 Broadcasting the User Study

In order to collect a larger amount of users (either for the laboratory or online study), we had to spread the study both by *word-of-mouth* and across some online platforms. We have tried to explore a platform whose unique goal is to deploy tasks for other humans to accomplish: "Mechanical Turk" (MTurk) from Amazon® could represent an interesting path, on performing studies which need fast grow and a large number of answers and providing scalability: there are studies which have been performed, not only in order to assess Visualization Design features [HB10], but also to extract color themes from images [LH13], relying on MTurk to provide participants. However, when we tried to probe into it, we have realized that *MTurk* at this time does not support Requesters from countries outside de United States, which is an obvious obstacle.

Therefore, we have opted for spreading the study across social networks like Facebook® or StumbleUpon. However, we found that gathering the laboratory users was a tough job to do, since many prospective users were not willing to fulfill the study. We also created a paid *FacebookAds* advertisement to boost the visits to our webpage, which was online for three days targeting users from Australia, Brazil, Central African Republic, China, India, Japan, Portugal, Russia, United States and South Africa. These countries were selected to represent each continent, with the goal of collecting a more representative cultural diversity to analyze. In the final phase of our study, we raffled a *FNAC*[1] Prize Card with 20 Euros to attract the final users.

Since the social networks were not providing the wanted amount of users, we explored a *Reddit* subthread called "Sample Size", which exists to disseminate user studies across the internet, which provided 159 new visitors to our webpage.

All these different broadcasting channels were monitored by a Google® Analytics piece of code embodied in each webpage.

4.2 Data Cleaning

Throughout the user study, we collected a **total amount of 477 users** which interacted with our study and fulfilled, at least, until the Color Vision Deficiencies Test Phase. However, only **259 users went on to the core phase of the study**, representing **54.29%** of the total amount, giving at least one answer on the set of 32 questions; the 218 users that did not leave an answer amount to **45.71%**. This large drop of users could be due to errors reported by the users, apparently the inability to submit answers when using the **Submit** button after rating the question; there were also some complaints when users tried to perform the study in some mobile devices (namely, the *iPhone® 6*), whereon the color slider was not able to be dragged and change the color value at the user will.

Concerning the percentage of users which showed up at the **laboratory trials, there were 28 users who performed the entire study**. On the other hand, there were **231 users which carried out the study online**. There was also a small sample of color vision deficient users which we will analyze in a qualitative manner; this set of users contains only one (1) user from the Laboratory Environment - **3.57%** of the sample size - and two online users - **less than 1%**. Lastly, we detected a small percentage of **six (6) users (2.59%) which did not presented a correct calibration of its LCD display**, evaluation based on the criteria referred before. The data presented and used in this dissertation document was gathered during roughly two months, from 15th of April until 8th of June. As said before, it was collected both with online and laboratory users, which was therefore stored in a Relational Database as previously explained in Section 3.2. In the end of the study, CSV files were exported from each table using a PostgreSQL client for macOS called *Postico*[2], which produced the files containing raw data to be cleaned and processed.

The refined tables were then divided into new and more specific ones so that we could detail our results analysis according to the goals defined before; the **Results** table was refined into <u>Laboratory Results</u>, <u>Online Results</u> and demographic results: concerning the age, we divided it on <u>Users aged below 20 Years Results</u>, <u>Users aged between 20 and 29 Years Results</u>, <u>Users aged between 30 and 39 Years Results</u>, <u>Users aged between 40 and 49 Years Results</u>, <u>Users aged between 50 and 59 Years Results</u> and <u>Users aged above 60 Years Results</u>. Respecting the division of genders, we created the categories <u>Female Users Results</u>, <u>Male Users Results</u> and <u>Other Gender Users Results</u>. We have **not**

[1] "Fnac, large retailer selling cultural and electronic products", Available at: `fnac.pt`. Last accessed on October 17th, 2016.

[2] Postico - a modern PostgreSQL client for the Mac, Available at: `eggerapps.at/postico/`. Last accessed on October 17th, 2016.

excluded neither the users which provided answer to only one question from the 32 question set, nor questions with only one color given when expecting an answer-pair; since the aim of this study was to collect the maximum amount of possible information from our users, these could provide useful and interesting inputs.

Dividing the results among smaller CSV files was the first step of the cleaning phase: the next checklist represents the detailed path which was followed to fulfill the data cleaning.

- **Remove ”hsl(..., 1, 0.50)”** - It was needed to remove the extra information which never varies from entry to entry of the table (remember Section 3.1). These values are the *Saturation* (S) and *Value* (V), primitives of the HSV Color Model used.
- **Format Values** - The value which remains to be formatted is simply the *Hue* (H), which is equal to a very precise position on the coded color slider on the interface; the value was composed of 14 decimal numbers and was rounded up to its closest integer number, then. Also, the *NONE* values needed to be replaced by 0, to simplify the processing of null answers.
- **Sort Entries** - In order to favor the iteration when processing the data, each line of the ”Results” Table was sorted according, firstly to the *Question ID*, and after by *User ID*.
- **Normalize Laboratory Data** - We have used a Spyder Color Calibrator to manage the color representation independently of the environmental conditions of light. Since the colors were adapted to be presented to each user, those same colors had to be trackbacked to the original color, for the sake of normalization of values. This is useful when comparing the results from this environment to the ”Online” Results, helping in data processing later.
- **Verify Duplicated Entries** - This step was performed only to ensure that the entries would not have any matching copy. As expected, there were not found any copies.
- **Normalize Profiling Info** - There were some entries which were written in Portuguese and other in English, depending on the language to perform the study chosen by the user. To avoid misleading profiling categories, all of the academic degrees were normalized to its corresponding name both in English and Portuguese. Also, the raw language values contained some specification of English dialects (*e.g.* en_US, en_UK), which was more information than we actually needed; these values were normalized to correspond only to its native and original language (like English, solely).
- **Sanitizing Users** - The entries which corresponded to a user that failed all 6 values from the Color Deficiencies Test Phase, would be deleted. Concerning the bad calibration values, it ”opened a window” to investigate the resilience of results when the calibration was not what it was expected - this will be covered in sub-Section 4.5.2. We have also separated their values from the regular users to perform a qualitative evaluation.

An example of clean data can be found in Table 4.1. The next step of data handling is processing it to prepare metrics, establish comparisons to pre-calculated answers and depict results in a CIE Chromaticity Diagram.

4.3 Data Processing

Processing the data was an important part of the process, since it was important to prepare the raw data collected and compute additional metrics which could be further analyzed to answer the raised questions. To perform this processing, we decided to implement a set of scripts in *Matlab* which could

User ID	Type	First Color	Second Color	Third Color	Drags	Time	Rating	Resets	Question ID
5713a02a13044	objTwoColors	#00FF00	0	137	459	56	2	0	17
573e4d0eb795b	objTwoColors	#00FF00	235	59	121	28	4	0	17
573edae85268b	objTwoColors	#00FF00	242	57	224	20	5	0	17
5740ad339507d	objTwoColors	#00FF00	228	67	205	14	3	0	17
573c70dabcfe0	objTwoColors	#00FF00	55	221	192	14	2	0	17
57582b17cd76a	twoColorsObj	#FF0000	#00FF00	#AF0049	724	65	2	0	18
573c783748e8b	twoColorsObj	#FF0000	#00FF00	#BFBE00	656	47	3	0	18
573e4022949b1	twoColorsObj	#FF0000	#00FF00	#B000FF	334	23	2	0	18
571151812791a	twoColorsObj	#FF0000	#00FF00	#C9B2A2	110	39	2	0	18

Table 4.1: Excerpt of Results Table, with clean data.

gauge the dataset of each question, demographic group and subset of users (non-calibrated and color vision deficient).

With this data processing, we intend to verify each answer-pair given by a certain user and compare the pairs with each other. It was important to separate the results by question ID, compare each questions' results with other questions that could conceive the same results, interpolate the values from each pair to check which color model ideal answers are closer to (either HSV, RGB, CMYK, CIE-L*a*b* or CIE-L*C*h*) and also, give meaning to each value, attributing a name to each color. All these parameters and computations are described in the next two subSections.

4.3.1 Data Preparation

Given the fact that questions had some differences between each other, there would have to be a cautious analysis; to achieve this, we developed a script for each question, each file contains the particular set of characteristics and specific comparisons and values of each question. Each question file is capable of computing the following datasets:

- **Laboratory Results** (Non-Color Vision Deficient Users and Color Vision Deficient Users);
- **Online Results** (Non-Color Vision Deficient, Color Vision Deficient and Uncalibrated Users);
- **Demographic Groups**, such as: Age and Gender groups according to the division previously established.
- **One-Component-White Answers** (this computation is only available for Questions 1 to 17).

All these datasets are analyzed by a block of code similar to the one in Appendix B; all iterations over each dataset start by verifying if any value contained in the answer pair is a white (*i.e.* zero valued) answer: if so, it is stored in a different table, along with all white answers. This was executed **only with non-daltonic users and calibrated users and it was not applied to any type of demographic group**, since its analysis is out of the scope of this thesis. This analysis is interesting, since we can understand if the users opted to leave one value as 0 to truly indicate a white color (to blend and create a lighter color), or simply because they didn't know what to blend.

Since the colors obtained in the color slider indicate values for the HSV Color Model, and the HSV provided different values from test to test, due to the changing calibration, it was mandatory to convert the color to a common color standard: for that reason, and since we had the generated color profiles with color information, the values were converted from HSV to CIE-XYZ Color Model. Thus, we can produce color blends in every studied color model (HSV, RGB, CMYK, CIE-L*a*b* and CIE L*C*h*) and ensure that colors obey to the same common standard; also, this is specially important to produce Chromaticity Diagrams where colors are mapped according to a set of XYZ primitives. Both answers were blended according to each color model referred before: for models which contained no angular values (RGB, CMYK and CIE-L*a*b*) it was only needed to linear interpolate the values for each primitive; but for models that have angular values (HSV and CIE-L*C*h have their Hue's value), it was needed to calculate the angular interpolation of their primitives.

$$
\begin{aligned}
R_{final} &= \frac{|R_{C1} - R_{C2}|}{2} + min(R_{C1}, R_{C2}); \\
G_{final} &= \frac{|G_{C1} - G_{C2}|}{2} + min(G_{C1}, G_{C2}); \\
B_{final} &= \frac{|B_{C1} - B_{C2}|}{2} + min(B_{C1}, B_{C2});
\end{aligned}
\tag{4.1}
$$

An example of linear interpolation between primitives can be seen on Equation 4.1, in which we blend Red, Green, Blue (RGB) primitives. The listing 1 shows how the angular interpolation is being calculated with our *Matlab* script. Afterwards, every resulting blending is **compared to the pre-calculated value**

```
diff_angles = abs(Hue_C1 - Hue_C2);
if diff_angles > 180
    angle_small = (360 - diff_angles);
    sum_major = max([Hue_C1 Hue_C2]) + (angle_small / 2));
    if sum_major > 360
        hue_final = rem((max([Hue_C1 Hue_C2]) + (angle_small / 2))), 360);
    else
        hue_final = max([Hue_C1 Hue_C2]) + (angle_small / 2));
    end
else
    hue_final = min([Hue_C1 Hue_C2]) + (diff_angles / 2);
end
```

Listing 1: Excerpt of *Matlab* code which interpolates the angular Hue value.

for each color model; the euclidean distance to the latter value is stored for statistical analysis. It is also **calculated the distance to the expected HSV values**, since the colors presented to the user were too calculated in HSV Color Model. Additional comparisons are: the colors blended in HSV are **compared to the reference color pairs of other questions which generate the same (or roughly) color**, to understand if our users tended to mix other pairs than the one expected for that question. To end these comparisons, the centroids of each set of colors mixed in every color model are calculated, along with their distance to the expected pre-calculated answer.

This computation is applied to all questions from 1 to 17, when a color is given and the users must provide two other colors that, in their opinion, were mixed to obtain the one provided. However, there are some differences when processing data from questions 18 to 32, which are questions where two colors are given and the user is expected to provide the color resulting from their blending, which implies a much simpler analysis due to only have to process one answer: there are no white answers to process (the ones which exist are excluded) and no colors to mix with each other; we only need to calculate the distance of the answered color, to the expected one.

4.3.2 Color Bins Comparison

This analysis phase had a very important step, which was to assign meaning to the answers given by the users: **to attribute commonly used names by the users, to colors indicated**. This is an interesting analysis to perform, since the users may have indicated various scattered values among a common color when, in fact, the users all wanted to indicate the same color (*e.g.* indicating many values around the Red Color, when they may wanted to simply indicate the color which corresponds to the name *Red*). Ideally, we would conduct a separated user study to perceive which names people normally attribute to colors; then we would gather all the data and analyze which were the most common names.

Luckily, the web page *XKCD*[3] had already conducted a widely large Color Survey[4] to study wich were the most common RGB color triples among users. They performed roughly more than 222 000 user sessions to ascertain color naming: they produced a map which shows the dominant names attributed to RGB colors over the faces of RGB cube (Appendix C), and they also produced a file comprised of 196 608 RGB triplets, grouped by Color Bins.

Color Bin	Frequency	Color Bin	Frequency
Black	1782	Lime-Green	878
Blue	37725	Magenta	990
Brown	10499	Maroon	3283
Cyan	2625	Mustard	711
Dark-Blue	2233	Navy-Blue	922
Dark-Brown	30	Olive	1336
Dark-Green	2927	Orange	9152
Dark-Purple	669	Pink	12627
Dark-Red	2	Purple	25747
Dark-Teal	163	Red	15474
Gold	49	Sky-Blue	32
Green	47858	Teal	9007
Light-Blue	2078	Yellow	7808
Light-Green	1		

Table 4.2: XKCD Color Bins.

Despite the fact XKCD's Color Survey was not a research realized with a scientific purpose, we decided to use it since it given its large sample size, and it was executed with a great amount of users which can verify it. We also found great compatibility between this survey and ours, since the values in the first were also presented in its maximum value of saturation (similar to our user study, in which we present colors in maximum hue). As said, these represent RGB triplets but, being our user results all in accordance with the CIE XYZ Color Model, we needed some cleaning and processing to match the data our responses. Using the sRGB color space, the default for computer screens and the one likely to have been used by the vast majority of the participants in the XKCD survey, we converted the RGB to CIE XYZ values and, then, divided all of the Color Bins in different tables; there are 27 names attributed to colors, some have more triplets (*e.g.* blue, green or purple), but some have a smaller set, which could mean greater agreement to assign names to colors. These bins of color are represented with their frequencies, in Table 4.2.

The idea was to compare our answers with each color bin, creating a mapping between our users' values and commonly-used names; in order to simplify and speed up the computation of the comparisons, each color bin was drawn and the smallest polygon formed by the set of triplets of each bin was used to compare the values (instead of comparing each answer with every triplet). Moreover, when processing these sets of RGB triplets, we left 3 color bins out of the game: *Black* since it has no expressivity in the Chromaticity Diagram, *Dark-Red* and *Light-Green* because they have very few triplets to be drawn.

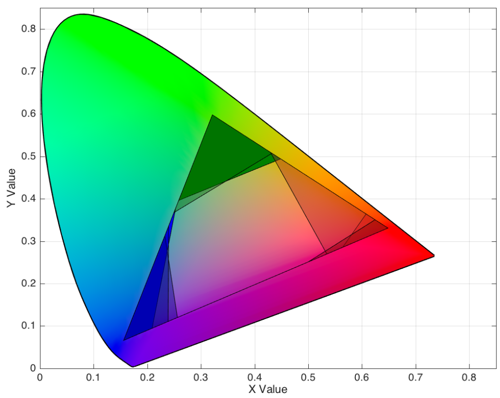

Figure 4.1: XKCD Color Survey: Color Bins Minimum Areas.

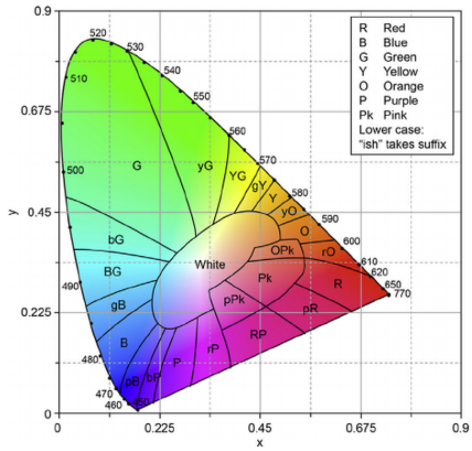

Figure 4.2: Approximate Color Regions on CIE 1931 Chromaticity Diagram. [FM97]

However, we expected that when these color bins were drawn on a chromaticity diagram, they would create independent and more comprehensive shapes: we found that there are overlapping values for some color bins (Figure 4.1), which ultimately complicates the analysis because there is more than one

[3] XKCD - Stick-Figure strip featuring humor about technology, science, mathematics and relationships, by Randall Munroe. Available at: `xkcd.com/`. Last accessed on October 17th, 2016.

[4] Color Survey Results. Available at: `blog.xkcd.com/2010/05/03/color-survey-results/`. Last accessed on October 17th, 2016.

possible name for the same color. For example, *Blue* and *Dark-Blue* share 5 triplets: (0,0,76), (0,0,77), (0,0,78), (0,0,79) and (0,0,80); *Green* and *Dark-Green* share only 1 triplet, (0,57,0). This could happen since there are colors which may have ambiguous names, or colors which are so close in the RGB cube that, for some users, it may be almost undetectable the difference between each shade. However, no repeated value was excluded from any color bin, since it would be invalid to remove the triplet from a certain color bin: for this to be fair, we would have to randomize the process, and it would not still be fair since the the triplet is valid in both color bins.

We have solved the problem by allowing the program to find only one of the names and look no more after finding it: this is not dramatic, since the detected overlaps are from color bins which are close to each other (the example from Green and Dark-Green, from above, is a valid one). Another way to detect the correct name is to observe the surrounding points around the value we are looking for, and attribute to that value the name which repeats the most in its neighborhood. Currently, we are detecting the color bin which could be associated to a given value by comparing the answer with the points which form the minimum polygon, testing if they are inside a given threshold ($threshold = 0.03$).

Moreover, the shapes created by each color bin can be depicted as **lines** if they present contiguous values in the same edge of the triangle, or as **triangles** if the values are near the corner of the triangle and are distributed along two edges. The late situation is represented in Figure 4.3. Alternatively, we could have opted for another kind of color name detection, but its implementation would be out of the scope of this Master thesis and would take a much longer analysis than the one performed. For instance, one could have gone identifying the colors by analyzing their values and processing the wavelength originated, comparing the resulting value with calculated areas, roughly defined by Fortner [FM97] and represented on Figure 4.2. This idea had one problem, which was the longevity of its solution (dated from 1997), and the inexistence of a ready-to-go implementation, completed with an *svg* with all areas defined, had added weight on the decision.

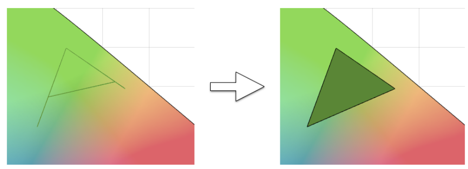

Figure 4.3: XKCD Color Bins: Transformation from line of points, to minimum polygon.

Another possible method to decode colors into names would be to interpret color values and associate a color temperature, being the late one compared against a well defined table of values; the problem here was the non-existence of table of well defined values of color temperature. Further investigation is needed to ascertain the possibility of creating such table.

4.3.3 Outputs Generated

Each script ends its execution when saving all the outputs referred below: it generates a set of CSV tables ready for being analyzed by SPSS Program, besides creating a great amount of CIE chromaticity diagrams to support the analysis. As referred before, questions 18 to 32 do not generate any output about white answers. The outputs produced are:

- Dataset Tables, for laboratory, online and demographic results, as well as the one-component white answers.

- CIE Chromaticity Diagrams, for laboratory, online and demographic results, as well as the one-component white answers. Particularly, we generate diagrams for each users group's answers, interpolated in RGB, HSV, CMYK, CIE-L*a*b* and CIE-L*C*h*.

4.4 Results

In the following Section, we perform a statistical analysis of the processed data obtained from the user study. The main data to be analyzed is the one obtained in the laboratory environment, being the online data only the corroboration of the main data. We start by drawing a profile of users who responded the survey, characterizing them as the age, country of residence, academic degree, along with other characteristics; after, we begin drafting answers to the questions raised in the beginning of study, also referred in Section 3.1, which comprises topics about *Color Mixtures*, *Color Models*, *Color Naming* and consider differences between *demographic groups*.

Note that each chromaticity diagram presented in this Section, shows a **black filled dot** which corresponds to the ideal answer for each color model, and **two black empty dots** which are the blending-basis of questions which have asked for it; the **grey dots** represent the answers given by the users, and the black lines represent the union between each grey dot, forming each answer pair given.

4.4.1 User Profile

As previously said in Section 4.2, we gathered a total amount of 259 users with, at least, one valid answer: from the laboratory environment we collected 28 users, and 231 from the online strand. All of these users gave valid answers for the Profiling, Calibration and Color Deficiencies Tests Phases: the information collected in the Profiling page is the most important to compose a user profile.

Recalling Section 3.2.1, we established that the most important information to collect were the *age*, the *gender*, *academic degree*, *nationality* and *country of residence*, as well as the *native language* of each user. The Table 4.3 represents the frequencies of genders, ages and academic degrees.

Environment	Users	Ages						Gender			Academic Degree					
		[0; 20[	[20; 29]	[30;39]	[40;49]	[50;59]	[60;90]	Female	Male	Other	College	High-School	Bachelor	Master	Doctor	NoDegree
Laboratory	28	0	17	5	3	1	2	10	18	0	0	5	13	10	0	0
Online	231	38	145	15	16	11	6	95	134	2	38	42	79	64	5	3
Total	259	38	162	20	19	12	8	105	152	2	38	47	92	74	5	3

Table 4.3: Results: Profiling Information (Gender and Academic)

As seen above, our user sample is composed by 259 (100%) users, being **105 (40.5%) Females**, **152 (58.7%) Males** and a minority of **2 (0.8%) Other gendered users**: this sample age can be characterized as being generally young ($\overline{x} = 29.77,\ \overline{x} = 23,\ s = 40.30$), surprisingly having **8 users (3.09%) aged above 60 years old** which could enhance some interesting differences between age groups. Generally, our users have hight academic qualifications, representing **66.02% of all users (Bachelor, Master and Doctoral Degrees)**, being **38 (14.67%) users qualified with College degree**, **47 (18.15%) have a High-School degree** and only **3 (1.16%) subjects do not presented any academic degree**. Between the laboratory and online environment, the distribution of users remains with the same proportions: more male users than females, mostly aged between 20 and 29 years old (60.71%) and the majority having a superior academic degree (46.43% BSc and 35.71% MSc).

Environment	Users	Nationality						Country of Residence						Languages		
		CA	ES	PT	UK	US	Others	CA	DE	GB	PT	US	Others	PT	EN	Others
Laboratory	28	0	0	27	1	0	0	0	0	0	28	0	0	28	0	0
Online	231	5	3	188	6	11	18	5	3	9	189	11	14	188	29	14
Total	259	5	3	215	7	11	18	5	3	9	217	11	14	216	29	14

Table 4.4: Results: Profiling Information (Nationalities, Countries of Residence and Languages)

The Table 4.4 depicts nationalities, current countries of residence and native languages spoken by our users. From the 259 (100%) participant users, **215 (83.01%) of them have Portuguese nationality**, **217 (83.78%) live in Portugal** currently and **216 (83.40%) speak Portuguese**; the second most influent group of users are the ones from english-speaking countries (United Kingdom, United States of America, and others). Other minor users which contributed to our survey came from Turkey, France, New Zealand, Sweden or even Antarctica (among others) - **these countries represent only 5.41%**. An ideal distribution of users would be such that it included enough users from all continents, which would give us room to investigate better the cultural implications on the results; another interesting aspect would be to have users from Countries contained in the United Nations' List of Least Developed Countries[5] included in the sample, which was not accomplished in this study since an isolated vietnamese user (0.39% of the user sample) contributed to the study.

4.4.2 Color Models

In this Section, we will start by analyzing the results from each question, comparing the statistics collected from each color model. Then, we are going to decompose the results by color models and evaluate which questions had the best and worst results. Along with the statistics we are going to present, in the end we are going to map them against the questions raised before, clearly identifying them whenever they are answered. We would like to emphasize that the important results are the ones collected in the laboratory environment: the online results will bridge and support the conclusions extracted from the laboratory conditions. The values presented as ”distances” are measured inside the finite interval $[0;1]$, since the CIE Chromaticity Diagram has its values comprised between this interval.

Question ID	Presented Color	Reference Pairs		Laboratory Environment					Online Environment				
		C1	C2	HSV	CIE-L*C*h*	CMYK	RGB	CIE-L*a*b*	HSV	CIE-L*C*h*	CMYK	RGB	CIE-L*a*b*
1	#FFFF00	Red	Green	0.13	0.2	**0.09**	0.12	0.12	0.07	0.21	**0.06**	0.07	0.07
2	#FF00FF	Red	Blue	0.22	0.16	**0.11**	0.17	0.16	0.15	0.16	**0.08**	0.1	0.12
3	#80FF00	Red	Cyan	**0.045**	0.215	0.05	0.095	0.11	**0.04**	0.21	0.06	0.11	0.11
4	#7F00FF	Red	Cyan	0.12					0.11				
5	#FF0080	Red	Magenta	0.17	0.15	**0.13**	0.14	0.14	0.16	0.15	**0.13**	0.14	0.11
6	#FF8000	Red	Yellow	0.07	0.13	0.06	0.08	**0.05**	0.03	0.14	0.03	0.04	**0.02**
7	#0000FF	Cyan	Magenta	0.16	0.23	**0.10**	0.15	0.17	0.13	0.18	**0.11**	0.17	0.22
8	#FF0000	Magenta	Yellow	**0.10**	0.17	**0.10**	0.13	0.13	0.10	**0.09**	0.12	0.14	0.16
9	#00FF80	Green	Cyan	0.13	0.16	**0.09**	0.10	0.11	0.11	0.13	**0.10**	**0.10**	0.11
10	#0080FF	Green	Magenta	0.30	0.26	**0.13**	0.21	0.20	0.17	0.27	**0.13**	0.20	0.22
11	#FF8000	Green	Magenta	**0.06**					**0.04**				
12	#80FF00	Green	Yellow	**0.11**	0.23	0.13	0.15	0.17	**0.08**	0.24	0.12	0.13	0.15
13	#0080FF	Blue	Cyan	0.27	**0.17**	0.19	0.25	0.23	0.14	0.20	0.14	**0.13**	0.14
14	#8000FF	Blue	Magenta	0.12	0.30	**0.10**	0.13	0.13	0.10	0.29	**0.09**	0.11	0.12
15	#00FF80	Blue	Yellow	0.09	0.30	**0.06**	0.11	0.13	0.11	0.30	**0.06**	0.11	0.13
16	#FF007F	Blue	Yellow	0.21					0.19				
17	#00FF00	Cyan	Yellow	0.07	0.16	**0.05**	0.10	0.11	0.08	0.17	**0.05**	0.10	0.11

Table 4.5: Distances between interpolated results in each Color Model, to the ideal pre-calculated answer.

As referred before, each answer pair given from our users on questions 1 to 17 (one color given, two colors asked) was interpolated in five color models: HSV, CIE-L*C*h*, CMYK, RGB and CIE-L*a*b*. Then, we have converted the result into CIE-XYZ values, so the comparison between the pre-calculated blend for each color model and the given answer-pair would be conveyed in a standard color model. However, since the CIE-XYZ color model represents a 3D color space and we are representing our values in the same plane of maximum saturation, the XYZ coordinates had to be flattened down to XY coordinates only, dropping the Z component: this is a conversion from CIE-XYZ to CIE-XYY, where the X and Y coordinates were divided by the sum of all XYZ coordinates. Then, the euclidean distance between this interpolated blend and the one pre-calculated was measured, indicating us the proximity of the user's answers to each color model. **It was this distance which we had considered when analyzing the relationship between the users' expectations and each color model**. In order to improve this analysis, we present Table 4.5 which contains the mean value for these distances, according

[5]"United Nations' List of Least Developed Countries, as of May 2016", Available at: `un.org/en/development/desa/policy/cdp/ldc/ldc_list.pdf`. Last accessed on October 17th, 2016.

to each color model for each question, in each study environment. Colored in green are, the color model which has the smallest distance, *per* question, in each environment.

Analyzing Questions

The importance of breaking down the evaluation into questions is such that, it is relevant to understand, at least, which color models have the best results for each mixture. The results from this Section will be critical to determine later which color models are more compatible with each mixture, which model yields better results and others who do not. In order to present the colors to the user, in the interface, we interpolated the colors from each color blending according to the HSV model, since it provides three parameters which are convenient for us to manipulate (the hue, saturation and value). Therefore, **the resulting colors which we present to the user when asking him the blending-basis are blended in HSV** for convenience. However, as said before, we intended to compare the interpolated answer pairs given by the users, to each of the previously referred color models: as it will be seen on each question below, we compared these answers with the pre-calculated values for each blending in each color model. For example, the answers were interpolated in CIE-L*C*h*, and then they were compared with the result which was supposed to happen when blending the two colors from that question, in CIE-L*C*h*.

On the other hand, when the blending-basis was given to the user and we intended to test which resulting color the users would tend to, we needed to give them every pre-calculated result, in every color model: this way, **we presented to the user the entire set of pre-calculated blending results, containing the results from HSV, CIE-L*C*h*, CMYK, RGB and CIE-L*a*b***.

The triples presented in tables below represent the resulting color of each color blending, *per* color model, and it is a XYZ Triple value that maps that color on the CIE Chromaticity Diagram.

Question One One can observe that the model which presents the lowest mean value is the CMYK ($\overline{x} = 0.09$), possibly indicating that this model yields the best results for this question, while HSV, RGB and CIE-L*a*b* have closer values. A Friedman Test showed that there are, indeed, significant differences ($\chi^2 = 48.568$, $p < 0.05$) between each color model. Further analysis with the Wilcoxon Test reveals that CMYK ($p < 0.05$) has, in fact, very different responses from the other color models, which leads us to conclude that **the CMYK Color Model is the best model to represent yellow blends**. Since HSV, RGB and CIE-L*a*b* have similar mean values, we tried to compare them between each other: **there is no statistically significant differences among HSV, RGB and CIE-L*a*b*, whereby there is insufficient information to evaluate this color models regarding this color mixture**. According to table, it is also possible to say that **CMYK Color Model presents a low deviation**, not only in laboratory results ($s_{lab} = 0.06$).

It is safe to say that **CIE-L*C*h* has the worst performance against the other color models**, since its mean is the highest of all ($\overline{x} = 0.20$), and the values from Wilcoxon Test ($p < 0.05$) indicates that this color model has statistically significant differences every other model. **These results are corroborated by the online users**, since a Wilcoxon Test shows that there are no statistically significant differences between the laboratory distances and online ones ($p < 0.05$).

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
1	(77, 93, 14)	Red	Green	(77, 93, 14)		(42, 42, 6)		(17, 20, 3)		(17, 20, 3)		(39, 42, 6)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				0.13	0.08	0.2	0.06	**0.09**	0.06	0.12	0.08	0.12	0.08
Distance to Objective - Online				0.07	0.09	0.21	0.07	**0.06**	0.06	0.07	0.09	0.07	0.08

Table 4.6: Question 1: expected colors, possible results and statistics of distances to Objective.

Question Two CMYK Color Model presents, yet again, the lowest mean value for distance to ideal answer ($\overline{x} = 0.11$). However, it is not safe to say that which color model had the worst results: judging by laboratory values, the HSV Color Model would not only the have highest mean distance, but also the largest deviation of answers; yet, evaluating the online results, it would CIE-L*C*h* to occupy such position. Performing a Friedman Test, we can conclude that there are, in fact, significant differences ($\chi^2 = 22.041$, $p < 0.05$) between the color models; post hoc Wilcoxon Analysis ($p < 0.05$) reveals CMYK has statistically different results from every other color model, therefore concluding that **CMYK has the best solution for this blending**.

The tendency of results to blend Magenta in CMYK Color Model, could be explained by the fact that magenta is a primitive color of such model, therefore leading the user to blend it accordingly. In this question, **CIE-L*C*h* has only significant differences with HSV ($p < 0.05$)**, which is far opposite from question 1. The online results for this question validate the laboratory experience, since a Wilcoxon Test show that there are no statistically significant differences between the laboratory distances and online ones ($p < 0.05$).

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
2	(59, 28, 97)	Red	Blue	(59, 28, 97)		(44, 22, 22)		(13, 6, 21)		(13, 6, 21)		(29, 14, 25)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				0.22	0.13	0.16	0.09	**0.11**	0.06	0.17	0.11	0.16	0.08
Distance to Objective - Online				0.15	0.13	0.16	0.08	**0.08**	0.04	0.1	0.08	0.12	0.05

Table 4.7: Question 2: expected colors, possible results and statistics of distances to Objective.

Question Three It is observable that CMYK Color Model presents the lowest mean value for distance to ideal answer ($\overline{x} = 0.05$); however, the standard deviation for the HSV Color Model is the highest between both study environments ($s = 0.12$). Running the Friedman Test, we can conclude that there are significant differences ($\chi^2 = 84.448$, $p < 0.05$) between the color models; Wilcoxon Analysis ($p < 0.05$) reveals that CMYK has statistically different results from other color models (except RGB), therefore concluding that **CMYK has the best solution for this blending**. CIE-L*C*h* is again the lower color model being significantly different from every other color model.

Once again, these results are validated by the online users' dataset, since a Wilcoxon Test show that there are no statistically significant differences between the laboratory distances and online ones ($p < 0.05$).The results from this question will be useful later, when analyzing question twelve.

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
3	(45, 76, 12)	Red	Cyan	(45, 76, 12)		(31, 44, 8)		(21, 22, 24)		(21, 22, 24)		(47, 44, 27)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				0.094	0.12	0.23	0.06	**0.061**	0.03	0.11	0.06	0.12	0.04
Distance to Objective - Online				**0.07**	0.09	0.23	0.06	**0.07**	0.03	0.12	0.06	0.13	0.04

Table 4.8: Question 3: expected colors, possible results and statistics of distances to Objective.

Question Four This one is the second possible output from the blend of Red and Cyan colors. Comparing the results for the HSV Color Model of both questions, mean distances are quite lower for question thirteen ($\overline{x} = 0.045$), whilst the deviation of answers is higher in both questions.

Based on these results, we can conclude **users tend to blend in CMYK Color Model to obtain a green color**, **mixing red and cyan does not generate a purple shade, according to users' expectations**. **These results are corroborated by the online users**, since a Wilcoxon Test show that there are no statistically significant differences between the laboratory distances and online ones ($p < 0.05$).

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
4	(27, 12, 95)	Red	Cyan	(59, 28, 97)		(31, 44, 8)		(21, 22, 24)		(21, 22, 24)		(47, 44, 27)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				0.12	0.13	0.20	0.06	**0.10**	0.04	0.19	0.06	0.20	0.09
Distance to Objective - Online				0.11	0.15	0.22	0.08	**0.11**	0.04	0.21	0.08	0.23	0.10

Table 4.9: Question 4: expected colors, possible results and statistics of distances to Objective.

Question Five It is observable that CMYK Color Model presents, the lowest mean value for distance to ideal answer ($\overline{x} = 0.13$), whilst its standard deviation is also the lowest between both study environments. Judging by laboratory and online values, every color model have closer values from each other, being the standard deviation the differentiator between them. The HSV Color Model has not only the have highest mean distance, but also the largest deviation of answers; yet, evaluating the result from Friedman Test, we can conclude that there are, in fact, significant differences ($\chi^2 = 32.720$, $p < 0.05$) between the color models; post hoc Wilcoxon Analysis ($p < 0.05$) reveals CMYK only has statistically different results from HSV color model, and RGB and CIE-L*a*b* have both statistically significant differences with HSV.

Every color model studied yield acceptable results when blending red and magenta. **The confirmation of similarity of values with the online users**, can be achieved performing a Wilcoxon Test, showing that there are no statistically significant differences between the laboratory distances and online ones ($p < 0.05$).

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
5	(45, 23, 22)	Red	Magenta	(45, 23, 22)		(45, 23, 22)		(45, 23, 22)		(45, 23, 22)		(45, 23, 25)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				0.17	0.10	0.15	0.08	**0.13**	0.07	0.14	0.09	0.14	0.08
Distance to Objective - Online				0.16	0.13	0.15	0.07	**0.13**	0.06	0.14	0.10	0.11	0.07

Table 4.10: Question 5: expected colors, possible results and statistics of distances to Objective.

Question Six It is observable that CIE-L*a*b* Color Model presents, the lowest mean value for distance to ideal answer ($\overline{x} = 0.05$). Judging by laboratory and online values, every color model have closer values from each other, being the standard deviation the differentiator between them. In fact, **HSV, CMYK and RGB have similar values due to the similarity between their outputs**: their mean values, though not the lower ones, are still very good and closer to the objective colors ($\overline{x}_{CMYK} = 0.06$, $\overline{x}_{HSV} = 0.07$ and $\overline{x}_{RGB} = 0.08$).

The CMYK Color Model has, again, the lowest deviation of results. Performing a Friedman Test, we can conclude that there are, in fact, significant differences ($\chi^2 = 45.396$, $p < 0.05$) between the color models; post hoc Wilcoxon Analysis ($p < 0.05$) reveals CIE-L*a*b* only has no statistically different results from CMYK color model, and CIE-L*C*h* has statistically significant differences with every color model. Every color model besides CIE-L*C*h offers great results, which leads us to allege that **HSV, RGB, CMYK and CIE-L*a*b* color models provide quite good results when blending red and yellow. These results are corroborated by the online users**, since a Wilcoxon Test show that there are no statistically significant differences between the laboratory distances and online ones ($p < 0.05$).

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
6	(49, 37, 5)	Red	Yellow	(49, 37, 5)		(54, 46, 6)		(49, 37, 5)		(49, 37, 5)		(54, 47, 6)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				0.07	0.10	0.13	0.09	0.06	0.06	0.08	0.09	**0.05**	0.07
Distance to Objective - Online				0.03	0.05	0.14	0.07	0.03	0.03	0.04	0.05	**0.02**	0.03

Table 4.11: Question 6: expected colors, possible results and statistics of distances to Objective.

Question Seven It is observable that CMYK Color Model proves to be again the lowest mean value for distance to ideal answer ($\overline{x} = 0.10$), whilst offering the lowest value for deviation along with CIE-L*a*b* ($s = 0.08$). CIE-L*C*h* has the highest mean result of distances, but the one which has the highest deviation is the HSV Color Model. Performing a Friedman Test, we can conclude that there are, in fact, significant differences ($\chi^2 = 60.886$, $p < 0.05$) between the color models; Wilcoxon Analysis ($p < 0.05$) shows HSV has no statistically different results from any color model and CIE-L*C*h* has statistically significant differences only with CMYK color model. In general, this question gathers a low quantity of statistically significant differences: between CIE-L*C*h* and CMYK, CMYK and RGB, and CMYK and CIE-L*a*b*

Based on these results, corroborated by the online users with a Wilcoxon Test that shows that there are no significant differences ($p < 0.05$), we can conclude **users tend to blend in HSV to obtain a blue color**. However, it should be considered that **HSV, RGB and CIE-L*a*b* also yielded good results, particularly the last one which had the lowest deviation of answers**. The results from this question can be found in Table 4.12.

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
7	(18, 7, 95)	Cyan	Magenta	(18, 7, 95)		(39, 49, 102)		(35, 27, 98)		(35, 27, 98)		(56, 50, 101)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				0.16	0.21	0.23	0.10	**0.10**	0.08	0.15	0.13	0.17	0.08
Distance to Objective - Online				0.13	0.21	0.18	0.08	**0.11**	0.06	0.17	0.11	0.22	0.07

Table 4.12: Question 7: expected colors, possible results and statistics of distances to Objective.

Question Eight The CMYK and HSV Color Model present the lowest mean value for distance to ideal answer ($\overline{x} = 0.10$), whilst standard deviation for the CMYK Color Model is also the lowest between both study environments. Surprisingly, CIE-L*C*h has the lowest result for the mean distance of online results ($\overline{x} = 0.09$), which is quite lower than the maximum value of this parameter in the online environment ($\overline{x}_{lab} = 0.16$). This result is different from the laboratory data, in which this same color model has the highest mean value for distance to ideal answer. With this said, **it is not safe to say that which color model had the worst results**. Also, there should be some sort of affinity between RGB and CIE-L*a*b* models, regarding the Laboratory: they both have the same mean distance and deviation values. Evaluating the data with the Friedman Test, we can conclude that there are, in fact, significant differences ($\chi^2 = 27.377$, $p < 0.05$) between the color models; a Wilcoxon Analysis ($p < 0.05$) does not reveal a significant difference between color models.

Every color model studied yield acceptable results when blending magenta and yellow, but further depth studying should be applied. **These results are corroborated by the online users**, since a Wilcoxon Test show that there are no statistically significant differences between the laboratory distances and online ones ($p < 0.05$).

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
8	(41, 21, 2)	Magenta	Yellow	(41, 21, 2)		(48, 32, 12)		(53, 38, 25)		(53, 38, 25)		(62, 51, 43)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				**0.10**	0.16	0.17	0.13	**0.10**	0.05	0.13	0.09	0.13	0.09
Distance to Objective - Online				0.10	0.17	**0.09**	0.12	0.12	0.05	0.14	0.07	0.16	0.07

Table 4.13: Question 8: expected colors, possible results and statistics of distances to Objective.

Question Nine CMYK and HSV Color Model present the lowest mean value for distance to ideal answer ($\overline{x} = 0.10$), whilst standard deviation for the CMYK Color Model is also the lowest between both study environments.

The results show that CIE-L*C*h* is the worst-generating values Color Model, having the higher mean value of all models across study environments. There is also the same tendency of RGB, CIE-L*a*b* and HSV present closer values between each other. Evaluating the data with the Friedman Test, we can conclude that there are significant differences ($\chi^2 = 48.252$, $p < 0.05$) between the color models; a Wilcoxon Analysis ($p < 0.05$) does reveal there are almost no significant difference between color models: mostly, the significant differences reside in CIE-L*C*h*, when compared again with CMYK, RGB and CIE-L*a*b*.

Every color model studied, except CIE-L*C*h*, yield acceptable results when blending green and cyan. **These results are corroborated by the online users**, since a Wilcoxon Test show that there are no statistically significant differences between the laboratory distances and online ones ($p < 0.05$).

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
9	(40, 73, 32)	Green	Cyan	(40, 73, 32)		(44, 75, 57)		(40, 73, 32)		(40, 73, 32)		(44, 75, 44)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				0.13	0.10	0.16	0.07	**0.09**	0.05	0.10	0.08	0.11	0.07
Distance to Objective - Online				0.11	0.08	0.13	0.06	**0.10**	0.04	**0.10**	0.08	0.11	0.06

Table 4.14: Question 9: expected colors, possible results and statistics of distances to Objective.

Question Ten The colors were interpolated and the mean values over distances were calculated, as Table 4.15 shows. It is observable that CMYK Color Model presents the lowest mean value for distance to ideal answer ($\overline{x} = 0.013$); its standard deviation is also the lowest between both study environments ($s = 0.05$), which could indicate a preference for this color model. Notwithstanding, all the mean values are substantially high when compared with previous questions, which could indicate that **none of these models produce the color blending according to the users' expectations, nor blending green and magenta to produce a blue shade**.

Running the Friedman Test, we can conclude that there are significant differences ($\chi^2 = 37.700$, $p < 0.05$) between the color models; a Wilcoxon Analysis ($p < 0.05$) reveals CMYK has statistically different results from other color model, therefore concluding that **CMYK has the best solution for this blending**, according to users' responses. HSV is the lower color model, being significantly different from every other color model excluding CMYK. CIE-L*C*h*, RGB and CIE-L*a*b* all afford similar mean values. Once again, these results are validated by the online users' dataset with a Wilcoxon Test providing no significant differences ($p < 0.05$). The results from this question will be useful later, when analyzing question thirteen. Figures 4.4 and 4.8 demonstrates the placement of answer-pairs, and the pairs blended in HSV Color Model.

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
10	(26, 23, 98)	Green	Magenta	(26, 23, 98)		(47, 33, 4)		(21, 22, 24)		(21, 22, 24)		(47, 48, 41)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				0.30	0.16	0.26	0.12	**0.13**	0.05	0.21	0.06	0.20	0.10
Distance to Objective - Online				0.17	0.17	0.27	0.09	**0.13**	0.04	0.20	0.04	0.22	0.07

Table 4.15: Question 10: expected colors, possible results and statistics of distances to Objective.

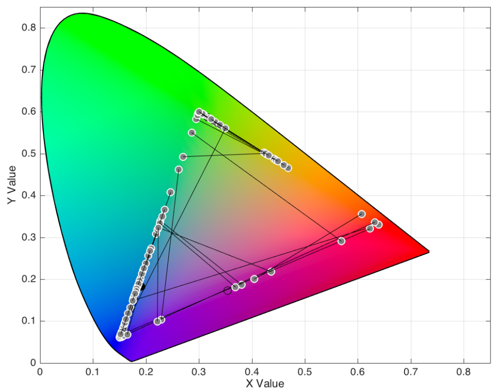

Figure 4.4: Online: Question 10, Regular users.

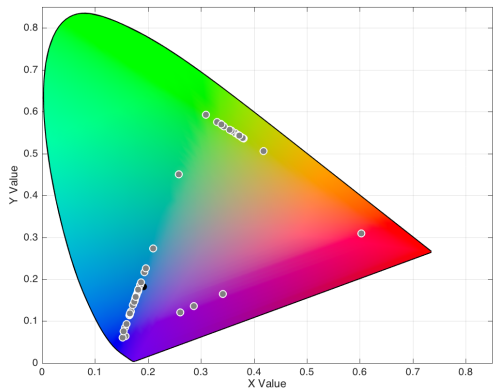

Figure 4.5: Online: Question 10, Regular users, mixed in HSV.

Question Eleven This question has the second possible output from the blend of Green and Magenta colors. Mean distances are dramatically lower for this question ($\overline{x} = 0.06$), whilst the deviation of answers is also lower. However, there is an interesting feature: instead of believing in a Green-Magenta blending to produce Orange, **the users tend to use again Red and Yellow** as on question six, which explains the low HSV mean value for question eleven. Based on these results, we can conclude **the orange color is a strongly implemented color in mental models of our users**. The results from this question can be found in table 4.16. Once again, **these results are corroborated by the online users**, since a Wilcoxon Test show that there are no statistically significant differences between the laboratory distances and online ones ($p < 0.05$).

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
11	(49, 37, 5)	Green	Magenta	(49, 37, 5)		(47, 33, 4)		(21, 22, 24)		(21, 22, 24)		(47, 48, 41)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				**0.06**	0.09	0.14	0.12	0.13	0.03	0.18	0.04	0.14	0.03
Distance to Objective - Online				**0.04**	0.06	0.12	0.10	0.14	0.02	0.19	0.02	0.15	0.01

Table 4.16: Question 11: expected colors, possible results and statistics of distances to Objective.

Question Twelve It is observable that HSV Color Model presents, the lowest mean value for distance to ideal answer ($\overline{x} = 0.11$), whilst standard deviation for the CMYK Color Model provides the lowest value between both study environments ($s_{lab} = 0.04$, $s_{online} = 0.05$). The results show that CIE-L*C*h* the worst-generating values Color Model; there is also the same tendency of RGB, CIE-L*a*b* and CMYK present closer values between each other. Evaluating the data with the Friedman Test, we can conclude that there are significant differences ($\chi^2 = 71.788$, $p < 0.05$) between the color models; a Wilcoxon Analysis ($p < 0.05$) does reveal **there are significant difference between color models**: when analyzing the results for the tests between HSV and other color models, it presents significant differences between all models except CMYK; the model which consistently presents the larger distances is CIE-L*C*h* against every color model, leading to statistically significant differences with every other model.

Comparing the results of this question with number three, we can observe that the later has shorter values: HSV Color Model still presents the best mean values between questions. The fact that question three has lower values, leads us to conclude that **mixing Red and Cyan to achieve this green tone is more similar with the users' expectations, than blending a Green and Yellow color**. Figures 4.6 and 4.7 compare the results from both question three and twelve, blended in HSV (the model which yields the best results).

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
12	(45, 76, 12)	Green	Yellow	(45, 76, 12)		(54, 81, 13)		(45, 76, 12)		(45, 76, 12)		(53, 81, 13)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				**0.11**	0.13	0.23	0.07	0.13	0.04	0.15	0.08	0.17	0.07
Distance to Objective - Online				**0.08**	0.11	0.24	0.06	0.12	0.05	0.13	0.09	0.15	0.09

Table 4.17: Question 12: expected colors, possible results and statistics of distances to Objective.

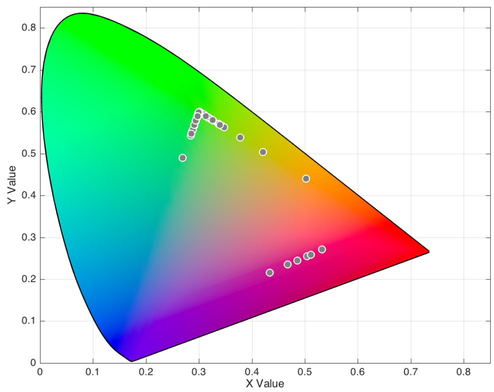

Figure 4.6: Online: Answers for Question 3, from regular users, mixed in HSV Color Model.

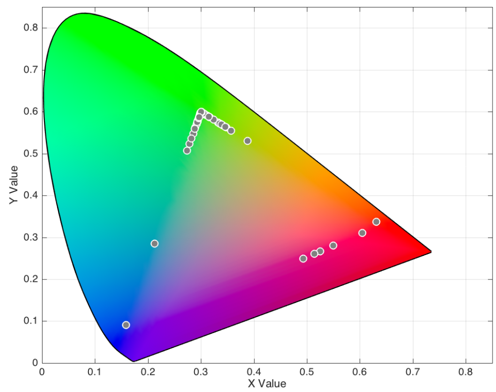

Figure 4.7: Online: Answers for Question 12, from regular users, mixed in HSV Color Model.

Question Thirteen It is interesting to see CIE-L*C*h* overcoming the lowest result in the laboratory environment, against other color models which regularly had best results in previous questions; however, these results are not consistent with the online users, which indicated responses closer to the RGB Color Model ($s_{online} = 0.13$). Analyzing the laboratory results, it shows that HSV is the worst-generating values Color Model, having the higher mean value ($\overline{x}_{HSV} = 0.27$) of all models. When comparing it to the online dataset, HSV, CMYK and CIE-L*a*b* have all the same mean values. Evaluating the data with the Friedman Test, we can conclude that there are significant differences ($\chi^2 = 38.993$, $p < 0.05$) between the color models on the laboratory results; a Wilcoxon Analysis ($p < 0.05$) does reveal **there are significant difference between color models**: when analyzing the results for the tests between HSV and other color models, it presents significant differences between all models except CIE-L*C*h*.

Comparing the results of this question with number ten, we can observe that this question has shorter HSV value; however we know that HSV was not the lowest mean value on question thirteen These results leads us to conclude that **there are insufficient values to ascertain the best color model to achieve this blue tone**. Further studies are required to unveil the appropriate color model and clarify this matter. Figures 4.8 and 4.9 compare the results from both question ten and thirteen, blended in HSV and RGB respectively.

Moreover, these results are **not** corroborated by the online users, since a Wilcoxon Test show that there are indeed statistically significant differences between the laboratory distances and online ones ($p < 0.05$): namely between the CMYK distance values ($p = 0.041$) and RGB ($p = 0.005$).

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
13	(26, 23, 98)	Blue	Cyan	(26, 23, 98)		(33, 37, 100)		(26, 23, 98)		(26, 23, 98)		(32, 30, 99)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				0.27	0.16	**0.17**	0.10	0.19	0.13	0.25	0.16	0.23	0.12
Distance to Objective - Online				0.14	0.16	0.20	0.09	0.14	0.11	**0.13**	0.15	0.14	0.11

Table 4.18: Question 13: expected colors, possible results and statistics of distances to Objective.

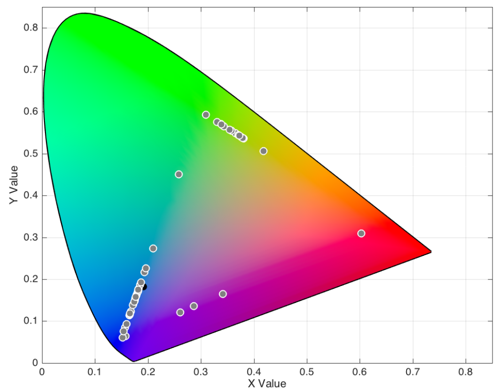

Figure 4.8: Online: Answers for Question 10, from regular users, mixed in HSV Color Model.

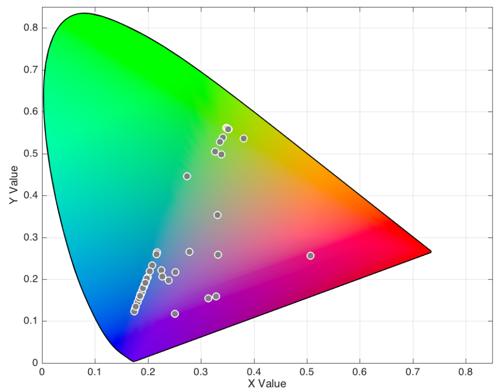

Figure 4.9: Online: Answers for Question 13, from regular users, mixed in RGB Color Model.

Question Fourteen It is observable that CMYK Color Model presents, the lowest mean value for distance to ideal answer ($\overline{x} = 0.10$ laboratory, and $\overline{x} = 0.09$ online), whilst standard deviation for the CMYK Color Model is also the lowest between both study environments presenting exactly the same value. The results show that CIE-L*C*h* the worst-generating values Color Model having, by far, the higher mean value of all models across study environments ($\overline{x} = 0.30$). There is also the same tendency of RGB, CIE-L*a*b* and HSV present closer values between each other. Evaluating the data with the Friedman Test, we can conclude that there are significant differences ($\chi^2 = 51.726$, $p < 0.05$) between the color models; a Wilcoxon Analysis ($p < 0.05$) does reveal there are no significant difference between color models: mostly, the significant differences reside in CIE-L*C*h*, when compared with HSV, CMYK and CIE-L*a*b*.

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
14	(27, 12, 95)	Blue	Magenta	(27, 12, 95)		(36, 16, 96)		(27, 12, 95)		(27, 12, 95)		(35, 16, 96)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				0.12	0.14	0.30	0.09	**0.10**	0.05	0.13	0.13	0.13	0.09
Distance to Objective - Online				0.10	0.12	0.29	0.13	**0.09**	0.05	0.11	0.12	0.12	0.09

Table 4.19: Question 14: expected colors, possible results and statistics of distances to Objective.

Evaluating this question, it is possible to affirm that **CMYK has the best results when mixing purple, a color derived from magenta**, due to the commitment between the mean value and standard deviation, which could be justified by the fact that **magenta is a primitive from such model, combined with the indication shown throughout the study to demonstrate a subtractive mental model of color**. **These results are corroborated by the online users**, since a Wilcoxon Test show that there are no statistically significant differences between the laboratory distances and online ones ($p < 0.05$).

Question Fifteen This question also presented a repeated color: this green shade is equal to the one presented in question nine, therefore its results are interesting to compare with this question. The colors were blended and the mean values over distances were calculated: it is observable that CMYK Color Model presents the lowest mean value for distance to ideal answer ($\overline{x} = 0.06$); its standard deviation is also the lowest between both study environments ($s = 0.03$). Though, it is important to analyze this result: since we are mixing opposite colors, both CMYK and RGB generate a neutral color, which means that the closer the users' answers are from the ideal answers (Blue and Yellow), the shorter the distance on these color models, and greyer the shade. **This value, in fact, supports the result of HSV Color** ($\overline{x}_{HSV} = 0.09$), which is very acceptable since the answer pairs are very close to the expected one.

Running the Friedman Test, we can conclude that there are significant differences ($\chi^2 = 63.068$, $p < 0.05$) between the color models; a Wilcoxon Analysis ($p < 0.05$) reveals that there are statistically different results among all color models, except for HSV and RGB and HSV and CIE-L*a*b*, which do not have statistically significant differences. Comparing the results of this question with number nine, we can observe that this question has shorter values: HSV Color Model still presents the best mean values between questions, and deviations of question 15 answers are lower for all models against question 9. This fact leads us to conclude that **mixing Blue and Cyan to achieve this green shade is more similar with the users' expectations, than blending a Green and Cyan color**. Figures 4.10 and 4.11 compare the results from both question nine and fifteen, blended in HSV (the model which yields the best results).

HSV has statistically different results from other color models, therefore concluding that **HSV has the best solution for this blending**. **The laboratory results are corroborated by the online ones**, since a Wilcoxon Test show that there are no statistically significant differences between the laboratory distances and online ($p < 0.05$).

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
15	(40, 73, 32)	Blue	Yellow	(40, 73, 32)		(43, 22, 10)		(21, 22, 24)		(21, 22, 24)		(41, 34, 42)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				0.09	0.04	0.30	0.08	**0.06**	0.03	0.11	0.05	0.13	0.06
Distance to Objective - Online				0.11	0.08	0.30	0.07	**0.06**	0.03	0.11	0.04	0.13	0.06

Table 4.20: Question 15: expected colors, possible results and statistics of distances to Objective.

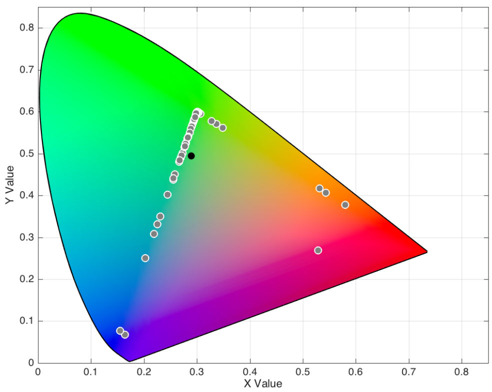

Figure 4.10: Online: Answers for Question 9, from regular users, mixed in HSV Color Model.

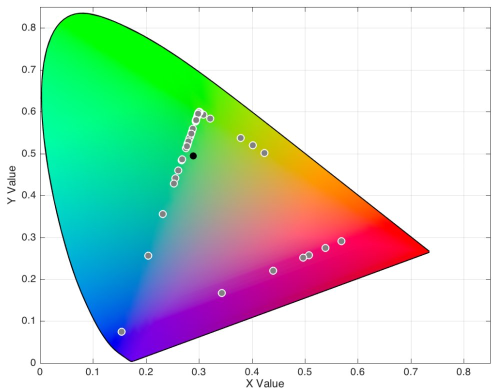

Figure 4.11: Online: Answers for Question 15, from regular users, mixed in HSV Color Model.

Question Sixteen Comparing the results for the HSV Color Model of both question 15 and 16, mean distances are largely high for question 16 ($\overline{x}_{lab} = 0.21$, $\overline{x}_{online} = 0.19$), whilst the deviation of answers is also lower in question 15. Whilst the color presented was fairly similar with Magenta, the users tended to answer with Red-Blue pair of colors (which, as seen on question two, produces magenta according to the HSV Color Model).

Based on these results, corroborated by the online users by a Wilcoxon Test with no significant differences ($p < 0.05$), we can conclude that **blending Blue and Yellow, according to users' mental model of color, produces Green instead of Magenta**. It is also possible to conclude that **to produce Magenta, according to user's mental model of color, it is needed to blend Red and Blue**. The results from this question can be found in Table 4.21. These differences can be seen on Figures 4.12 and 4.13, which largely demonstrate the placement of answer-pairs, and the pairs blended in HSV Color Model.

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
16	(45, 23, 22)	Blue	Yellow	(45, 23, 22)		(43, 22, 10)		(21, 22, 24)		(21, 22, 24)		(41, 34, 42)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				0.21	0.10	0.22	0.12	**0.10**	0.05	0.16	0.07	0.12	0.08
Distance to Objective - Online				0.19	0.12	0.17	0.09	**0.10**	0.06	0.15	0.07	0.11	0.06

Table 4.21: Question 16: expected colors, possible results and statistics of distances to Objective.

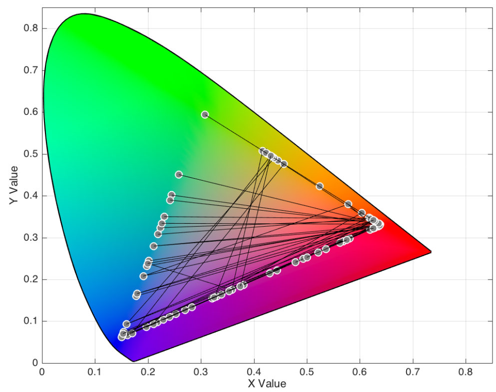

Figure 4.12: Online: Answers for Question 16, from regular users.

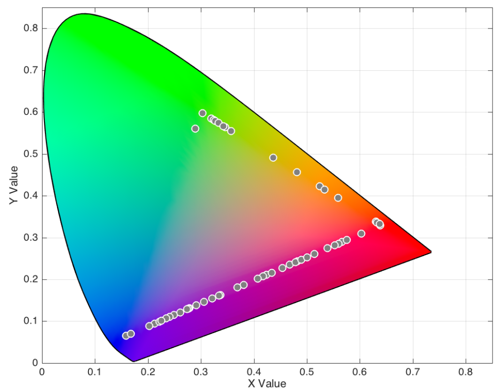

Figure 4.13: Online: Answers for Question 16, from regular users, mixed in HSV Color Model.

Question Seventeen Finally, the colors for this last question were blended: it is observable that CMYK Color Model presents the lowest mean value for distance to ideal answer ($\overline{x} = 0.05$ laboratory, and $\overline{x} = 0.05$ online), whilst standard deviation for the CMYK Color Model is also the lowest between both study environments presenting exactly the same value. The results show that CIE-L*C*h* the worst-generating values Color Model having the higher mean value of all models across study environments ($\overline{x} = 0.16$), which is consistent with the entire user study. There is also the tendency of RGB and CIE-L*a*b* to present closer values between each other. Evaluating the data with the Friedman Test, we can conclude that there are significant differences ($\chi^2 = 86.654$, $p < 0.05$) between the color models; a Wilcoxon Analysis ($p < 0.05$) does reveal there are clearly significant difference between color models: mostly, every color model has significant differences between each other, except for HSV-CMYK, and RGB-CIE-L*a*b* which in fact present no statistically significant differences.

It is possible to affirm that **CMYK has the best results when cyan and yellow**, which could be justified by the fact that **cyan and yellow are primitives from such model, combined with the indication shown throughout the study to demonstrate a subtractive mental model of color**. **These**

results are corroborated by the online users, since a Wilcoxon Test show that there are no statistically significant differences between the laboratory distances and online ones ($p < 0.05$).

Question ID	Given Color	Reference Pair		Possible Results									
		C1	C2	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
17	(36, 72, 13)	Cyan	Yellow	(36, 72, 13)		(49, 77, 47)		(49, 78, 33)		(49, 78, 33)		(66, 87, 46)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				0.07	0.10	0.16	0.06	**0.05**	0.02	0.10	0.06	0.11	0.05
Distance to Objective - Online				0.08	0.13	0.17	0.06	**0.05**	0.03	0.10	0.06	0.11	0.05

Table 4.22: Question 17: expected colors, possible results and statistics of distances to Objective.

Question ID	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
	Mean ($\overline{x}$)	Std-Dev (s)	Mean ($\overline{x}$)	Std-Dev (s)	Mean ($\overline{x}$)	Std-Dev (s)	Mean ($\overline{x}$)	Std-Dev (s)	Mean ($\overline{x}$)	Std-Dev (s)
1	0.1258	**0.08275**	0.2042	**0.0644**	0.0926	0.06118	0.1237	0.07925	0.1232	0.0807
2	**0.2173**	0.13014	**0.1573**	0.09445	0.106	0.05642	**0.166**	0.10521	0.156	0.08399
3	0.0941	0.12308	0.23	**0.05855**	0.0609	**0.03379**	0.1114	**0.06034**	0.1227	**0.03918**
4	0.1162	0.12975								
5	0.1683	0.10113	**0.15**	0.08	**0.1322**	0.06787	0.1389	0.09106	0.135	0.07579
6	**0.0741**	0.10418	**0.1332**	0.08671	**0.0577**	0.06164	**0.0777**	0.0973	**0.0509**	0.07374
7	0.1577	**0.20679**	0.2323	**0.10038**	0.0986	0.07523	0.1455	**0.12835**	0.1705	0.07925
8	0.0954	**0.16302**	0.17	**0.12845**	0.1008	**0.4974**	0.1292	0.08967	0.1292	0.08986
9	0.1258	0.0989	0.1642	0.07463	0.0911	0.04642	**0.1005**	0.07524	**0.1142**	0.06694
10	**0.3**	**0.15792**	**0.2557**	**0.1164**	**0.1314**	0.04769	**0.2107**	0.06403	**0.2043**	**0.09581**
11	**0.0587**	0.08828								
12	0.1067	0.12639	0.2343	0.06638	**0.1314**	0.03966	0.151	0.07758	**0.1743**	0.07284
13	**0.2713**	0.15607	0.1663	0.09701	**0.1875**	**0.13097**	**0.245**	**0.15795**	**0.2269**	**0.12224**
14	0.1186	**0.014423**	**0.2995**	0.08936	0.0973	**0.4901**	0.1327	**0.13406**	0.1336	**0.09444**
15	0.09	**0.03559**	**0.3031**	0.07872	**0.0625**	**0.02696**	0.11	**0.04705**	0.1256	**0.06229**
16	0.2087	0.10378								
17	**0.0683**	0.10228	0.1626	**0.05902**	**0.0452**	**0.0162**	**0.103**	**0.0574**	**0.113**	**0.05112**

Table 4.23: Laboratory: Statistics for distances *per* question, of Results Interpolated in each Color Model.

Analyzing Color Models

Now that we have broke down the results for each question, it is important to evaluate the values according to each color model. We have gathered the results from the previous Section, displaying the three best and worst results of each color model, identified as green and red, respectively: this information is presented in Table 4.23. Also, based on Table 4.5, which presents the mean values for each color model decomposed by question, we can run descriptive statistics over its column and produce Table 4.24 that is going to be helpful when inspecting the results *per* color model, which contains a set of descriptive statistics for each Color Model. In green/red, it is identified the color model which had the best/worst result for each statistic.

Descriptive Statistics	Laboratory Environment					Online Environment				
	HSV	CIE-L*C*h*	CMYK	RGB	CIE-L*a*b*	HSV	CIE-L*C*h*	CMYK	RGB	CIE-L*a*b*
Mean ($\overline{x}$)	0.14	**0.20**	**0.10**	0.14	0.14	0.11	**0.20**	**0.09**	0.12	0.13
Std-Dev (s)	**0.08**	0.06	**0.04**	0.05	**0.04**	**0.04**	**0.06**	**0.04**	**0.04**	0.05
Maximum Value	0.30	0.30	0.19	0.25	0.23	0.17	0.30	0.14	0.20	0.22
Minimum Value	0.05	0.13	0.05	0.08	0.05	0.03	0.09	0.30	0.04	0.02
Range	**0.25**	0.17	**0.14**	0.17	0.18	0.14	**0.21**	**0.11**	0.16	0.20
Variance (s^2)	**0.006**	0.003	**0.001**	0.002	0.002	0.002	**0.004**	**0.001**	0.002	0.003

Table 4.24: Condensed Statistics for Distances to Ideal Results, mixed in each Color Model. In Green/Red shade, the best/worst result for each descriptive statistic.

The Color Model which presented the lowest mean value for distances was the CMYK Color Model ($\overline{x} = 0.10$), followed by HSV, RGB and CIE-L*a*b* (all with $\overline{x} = 0.14$), being CIE-L*C*h the model which has the highest calculated distances ($\overline{x} = 0.20$). Consistently, the color model which has the lowest variance and range of answers is the CMYK ($s^2 = 0.001$, $range = 0.14$), opposed to the HSV ($s^2 = 0.006$, $range = 0.26$).

By analyzing the results from the online users, we can verify that they corroborate the smallest data set (from laboratory users). In pursuance of fully understanding which color model provides the best results, we are going to break down the results according to Color Models *per* question, describing it in the following sub-subSections.

HSV Color Model Blendings The HSV Color Model, along with CMYK and RGB, is the one which presents the lowest standard deviation of distances between the results from the online environment, which could indicate greater agreement between distances to the ideal HSV answer.

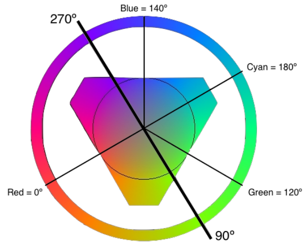

Figure 4.14: Example of HSV Hue Circle, with opposed hue values.

The questions which have shorter distances are number eleven (given orange and expected green and magenta), number seventeen (given green, expected blue and yellow) and number six (given orange, expected red and yellow), with mean values of $\overline{x} = 0.0587$, $\overline{x} = 0.0683$ and $\overline{x} = 0.0741$, respectively. On the other hand, we found that the questions which generate the worst results are number two (given magenta, expected red and blue), number thirteen (given a shade of blue, expected blue and cyan) and number ten (given a shade of blue, expected green and magenta), with correspondent mean values $\overline{x}_2 = 0.2173$, $\overline{x}_{13} = 0.2713$ and $\overline{x}_{10} = 0.3$. By analyzing Table 4.24, we can conclude that the HSV color model is the one which has a wider range of distances (laboratory environment) compared to other models.

When comparing the results from the HSV color model with other color models' results, we detected some statistically significant differences with other models: performing a Wilcoxon Test ($p < 0.05$), we can infer that HSV does have statistically significant differences with CIE-L*C*h*, CMYK, RGB and CIE-L*a*b* in the majority of questions. The model which HSV has least statistically significant differences with is RGB, with seven questions.

As referred before, there are some color blends that, due to the fact that primitives of the mixture are precisely opposed (180^o) in the HSV hue circle, the blending in HSV Model could produce two different outputs. This occurs if one mixes the colors obeying to a positive or negative rotation on the circle (as seen on Figure 4.14). There are in this study three pairs of colors which blend onto two possible colors: pair Red-Cyan (with possible outputs question three and four), pair Green-Magenta (questions ten and eleven) and pair Blue-Yellow (questions fifteen and sixteen). By placing these questions, we intended to understand which side the user would tend to follow (or even if he follows one) when asked to indicate the blending-basis. The results for each question were already analyzed in the previous subSection, therefore we present the essence of them in the following topics:

1. Red & Cyan Blend - Analyzing answers for questions three and four, they produce fairly similar results: they are both a bit far from the reference pair ($\overline{x}_{distance-3} = 0.0941$ and $\overline{x}_{HSV-4} = 0.1162$), although the mean distance to the HSV pre-calculated blending for question three has a slightly lower value than question four. This could be also compared to question 12, which also produces **Lime-Green** like question three, but even when compared, question three still has the best results when generating this tone of green. This leads us to specify that, although the mean distances to the ideal HSV Color blend for this mixture, are not the lowest among all questions, **the users show a tendency to associate the blending of red and cyan to a result of lime-green, instead of shade of purple**. When comparing these results with online, we found that the later ones corroborate and prove this conclusion.

2. <u>Green & Magenta Blend</u> - Unlike the previous blend, the results between these questions were quite different between each other concerning the distance to the reference pair: $\overline{x}_{HSV-10} = 0.3$ and $\overline{x}_{HSV-11} = 0.0587$. However, the lower results associated with question eleven are due to the simple fact that **users indicated answers pairs which contained Red and Yellow**, which is the pair analyzed previously that also blended into orange; if the distance to the ideal answer pair for this question was measured, its mean value would be $\overline{x}_{distanceC1-C2} = 0.645$, which is largely different from the reference pair. Therefore we can conclude that **it is hard for the users to blend green and magenta, to obtain either a blue or an orange shade**; we can also conclude that **the blending of red and yellow onto an orange color, is a strongly implemented color mixture, in mental models of our users**.

3. <u>Blue & Yellow Blend</u> - Evaluating the results obtained on question fifteen and sixteen, we obtain different results for both. Analyzing results of question fifteen, we know that the distance to the expected pair of colors it presents one of the lowest values among all results for HSV Color Model ($\overline{x}_{HSV-15} = 0.09$, $s_{HSV-15} = 0.03559$); however, when comparing the result-pairs given on this question, with the ones given on question nine (which presented the exact same shade of green, when asked for pair Green-Cyan), question fifteen still presents the results to generate this color. As it can be seen on Figure 4.15, the resulting blend in HSV Color Model tend to be close to the ideal HSV answer: despite being nearer to the top corner of the HSV Model Triangle, **we can still consider the answers to be a tone of green color**. Regarding the results from question 16, they present themselves to be one of the worst for this color model: the distance to the reference pair is $\overline{x}_{HSV-16} = 0.2087$ and the standard deviation for the distances of answers blended in HSV is $s_{HSV-16} = 0.10378$. Since the presented color had a strong value of red component, users tended their answers to the red shade, while blending it with a purple or pink one, to indicate a mixture close to magenta. This indicates that **blending Blue and Yellow, in HSV Color Model, does not correspond to a red shade, but to a green one, according to the users' expectations**.

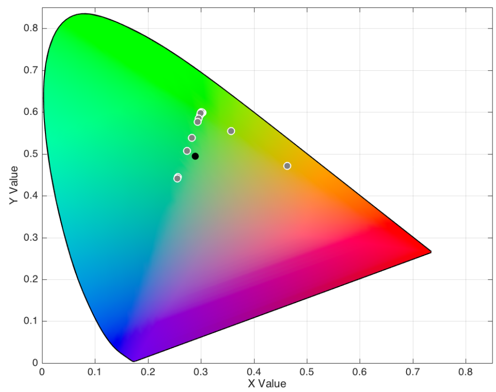

Figure 4.15: Laboratory: Answers for Question 15, from regular users, mixed in HSV Color Model.

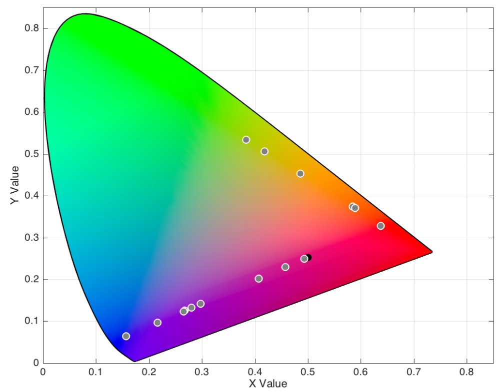

Figure 4.16: Laboratory: Answers for Question 16, from regular users, mixed in HSV Color Model.

Another interesting example are Question 10 and 13: they both present a shade of blue, which could be obtained by two combinations, either Green and Magenta (Question ten) or Blue and Cyan (Question thirteen). Particularly, the late question had a fairly simple expected pair (two shades of blue), but the users demonstrated some dispersion when answering the question: moreover, the statistics prove it, by having a rather high standard deviation ($\overline{x}_{HSV-10} = 0.3$, $s_{HSV-10} = 0.15792$) when compared to the standard deviation of the whole model ($s_{HSV} = 0.08$). These results are, thus, consistent with the know fact revealed in the Background of this thesis that **human color perception is poorer in the blue**

region of the color spectrum, than in others, *e.g* the green zone, which produced the best results for this color model; these results are extensible to the purple region of the spectrum, which is contiguous to the blue one.

The diagram of Figure 4.17 contains the three top and bottom-valued questions, disposed on top of an interval $[0; 0.5]$ of differences. Each question is mapped according to its mean value for distance to the ideal HSV Color Model response, while is accompanied by the range of values which compose its answers.

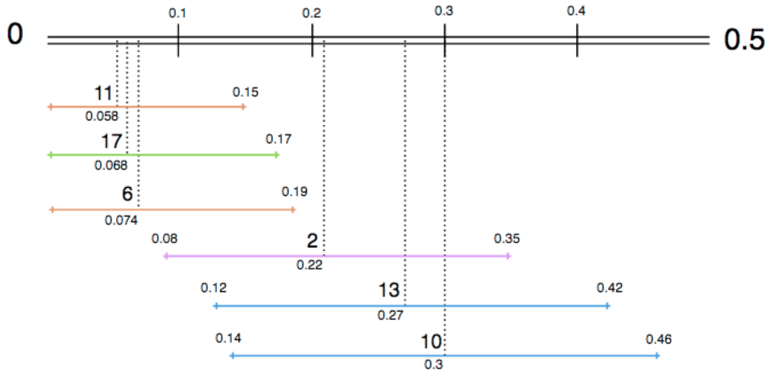

Figure 4.17: Best and Worst Questions, according to HSV Color Model.

<u>**CIE-L*C*h* Color Model Blendings**</u> In turn, the CIE-L*C*h* Color Model is the one which presents the worst results for most of the descriptive statistics present on Table 4.24: it has the highest mean value on laboratory and online environment, and the highest standard deviation, range and variance exclusively on the online environment.

The three questions which have shorter distances are number six (given orange, expected red and yellow), number five (given a shade of red, expected red and magenta) and number two (given magenta, expected red and blue). The mean values distances for this questions were $\overline{x}_6 = 0.1332$, $\overline{x}_5 = 0.15$ and $\overline{x}_2 = 0.1573$ which, contrary to the previous color model, are all values above 0.1 (a quite high value in the scale which results are presented), that could represent a significant change in the resultant color.

On the other hand, we consider that the questions which generate the worst results are number ten (given a shade of blue, expected green and magenta), number fourteen (given a shade of purple, expected blue and magenta) and number fifteen (given a shade of green, expected blue and yellow), with correspondent mean values $\overline{x}_{10} = 0.2557$, $\overline{x}_{14} = 0.2995$ and $\overline{x}_{15} = 0.3031$. Curiously, the standard deviations of distances (for the laboratory environment) in this color model are fairly low when compared to the previous color model.

When comparing the results from the CIE-L*C*h* color model with other color models' results, we detect some statistically significant differences with other models: performing a Wilcoxon Test ($p < 0.05$), we can infer that CIE-L*C*h* does present statistically significant differences with HSV, CMYK, RGB and CIE-L*a*b* in the majority of questions (between 8 to 10 questions). The model which CIE-L*C*h* has most statistically significant differences with is CMYK, with eleven questions.

Question six presented again a constant top value for the mean value, on this model, which reinforces the theory that the **orange color is commonly used and mixed by the users**. On the other hand, question number ten kept having one of the worst mean ($\overline{x}_{10} = 0.2557$) and deviation ($s_{10} = 0.1164$) values, strengthening the theory that **blue shades and tones will probably wild worst results, due to the fact that it is the color which human have less descriptive power**.

The question which revealed one of the lowest standard deviation value (meaning less oscillation of results), relating the online environment, was question three ($s_3 = 0.05855$): this question help us illustrate the difference between each of the descriptive statistics, since it has one of the highest mean

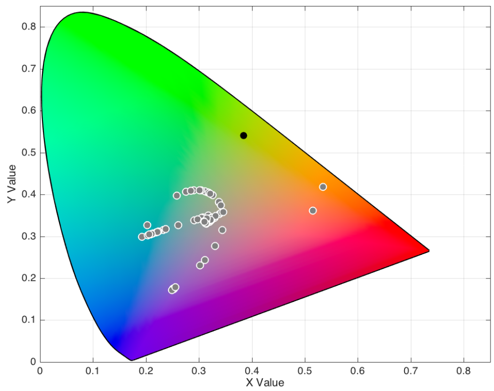

Figure 4.18: Online: Answers for Question 3, from regular users, mixed in CIE-L*C*h* Color Model.

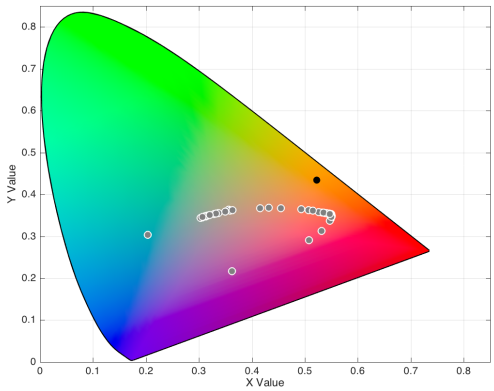

Figure 4.19: Online: Answers for Question 6, from regular users, mixed in CIE-L*C*h* Color Model.

value of distances ($\overline{x}_{17} = 0.23$) and, at the same time, lowest standard deviation. This could portray a scenario in which the users agreed on a quite distant answer. This question is illustrated in Figure 4.18.

The question which has the lowest mean value of distances was question six ($s_{LCh-6} = 0.1332$), and it is represented on Figure 4.19. Nonetheless, we can observe that **these questions have all answers pairs which, when blended according to CIE-L*C*h*, generate results that are farther apart from the ideal answer of each question**, therefore concluding that **CIE-L*C*h* is not the color model which hatches the best results when blending colors, according to users' expectations**.

The diagram of Figure 4.20 contains the three top and bottom-valued questions, disposed on top of an interval $[0; 0.5]$ of differences. Each question is mapped according to its mean value for distance to the ideal CIE-L*C*h* Color Model response, while is accompanied by the range its answers.

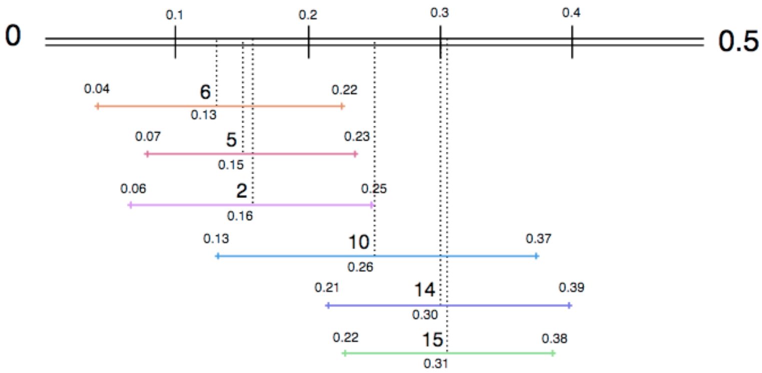

Figure 4.20: Best and Worst Questions, according to CIE-L*C*h* Color Model.

<u>**CMYK Color Model Blendings**</u> The CMYK Color Model is, by far, the one which presents the best results for most of the descriptive statistics present on Table 4.24: it has the lowest mean value of distances ($\overline{x}_{lab} = 0.10$, $\overline{x}_{online} = 0.09$), lowest standard deviation ($s_{lab} = 0.04$, $s_{online} = 0.04$), the lowest range of values ($range_{lab} = 0.14$, $range_{online} = 0.11$) and, finally, the lowest variance value ($s^2_{lab} = 0.001$, $s^2_{online} = 0.001$).

The three questions which have shorter distances are number seventeen (given a green, expected cyan and blue), number six (given orange, expected red and yellow) and number fifteen (given a shade of green, expected blue and yellow). The mean values distances for this questions were $\overline{x}_{17} = 0.0452$, $\overline{x}_6 = 0.0577$ and $\overline{x}_{15} = 0.0625$ which, contrary to the previous color model, are all values <u>below 0.1</u>, that does not represent a significant change in the resultant color.

On the other hand, we consider that the questions which generate the worst results are number ten (given a shade of blue, expected green and magenta) and twelve (given a tone of green, expected green and yellow), number five (given a shade of red, expected red and magenta) and number thirteen (given a shade of blue, expected blue and cyan), with correspondent mean values $\overline{x}_{10-12} = 0.1314$, $\overline{x}_5 = 0.1322$ and $\overline{x}_{13} = 0.1875$. Comparing them with the CIE-L*C*h* Color Model, we can easily observe that these values are very low when compared with the later's worst results.

Question six keeps presenting a constant top value for the mean value, on this model, while question number ten and thirteen (both presented blue shades) kept having the worst mean and deviation values ($\overline{x}_{13} = 0.1875$, $s_{13} = 0.13097$), strengthening the theories aforementioned.

When comparing the results from the CMYK color model with other color models' results, we detect some statistically significant differences with other models: performing a Wilcoxon Test ($p < 0.05$), we can infer that CMYK does present statistically significant differences with HSV, CIE-L*C*h*, RGB and CIE-L*a*b* in the majority of questions. The model which CMYK has most statistically significant differences with is RGB, with thirteen questions.

Question seventeen presented consistently another low value: along with question three and fifteen, these presented different shades of green and all had yielded favorable results. Having this in mind, this may lead us to form another conclusion: **questions which presented shades of green color may produce better results, according to users' expectations**. This is consistent with the fact that **humans have more descriptive power in the green zone of the spectrum, due to the amount of cones which exist in the human eye**.

As it was explained before in the theoretical background, this color model is mainly a subtractive one, meaning it will naturally darken the colors when they are blended; the questions which yielded **better results are majorly related to primitives of the CMYK color model**. This success could be related to the fact that **people tend to formulate mental models of color based on ink mixing in childhood** [GC04], mostly associating it to RYB and CMYK Color Models without even knowing it.

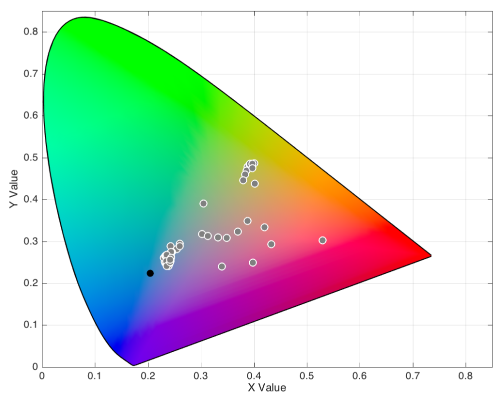

Figure 4.21: Online: Answers for Question 13, from regular users, mixed in CMYK Color Model.

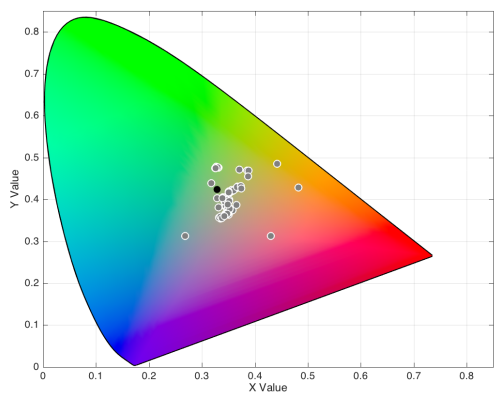

Figure 4.22: Online: Answers for Question 17, from regular users, mixed in CMYK Color Model.

These results indicate that **CMYK is a highly compatible color model with the users expectations**, as this model presents statistics which prove that CMYK had smaller distances to ideal answers and lower deviation of answers. Figure 4.21 represents the results of Question 13, which had wider distances to the pre-calculated CMYK blend, and Figure 4.22 show the results for Question 17, the question with closer distances. The diagram of Figure 4.23 contains the three top and bottom-valued questions, disposed on top of an interval $[0; 0.5]$ of differences. Each question is mapped according to its mean value for distance to the ideal CMYK Color Model response, while is accompanied by the range of values which compose its answers.

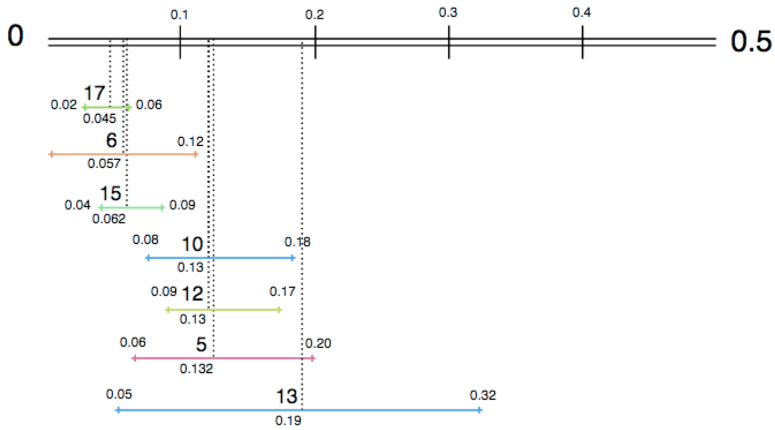

Figure 4.23: Best and Worst Questions, according to CMYK Color Model.

<u>**RGB Color Model Blendings**</u> This color model, as covered before, is complementary to the CMYK color model. Feedback collected from the users was such that, sometimes, the users which knew how to blend in subtractive color models, tended to be confused and tried to mix additive color models, also. Based on the results collected from the laboratory users, we can tell that the results from this color model are quite similar to CMYK results: the descriptive statistics present on Table 4.24, prove RGB has one of the lowest mean value of distances ($\overline{x}_{lab} = 0.14$, $\overline{x}_{online} = 0.12$) and one of the lowest standard deviations ($s_{lab} = 0.05$, $s_{online} = 0.04$ equal to $s_{CMYK-online}$).

The three questions which have shorter distances are number number six (given orange, expected red and yellow), number nine (given a shade of green, expected green and cyan) and seventeen (given a green, expected cyan and blue). The mean values distances for this questions were $\overline{x}_6 = 0.0777$, $\overline{x}_9 = 0.1005$ and $\overline{x}_{17} = 0.1030$. On its turn, we consider that the questions which generate the worst results are number two (given magenta, expected red and blue), number ten (given a shade of blue, expected green and magenta) and, again, number thirteen (given a shade of blue, expected blue and cyan), with correspondent mean values $\overline{x}_2 = 0.1660$, $\overline{x}_{10} = 0.2107$ and $\overline{x}_{13} = 0.2450$. Comparing them with the CIE-L*C*h* Color Model, we can observe these values are likely to be similar when compared with the later's worst results, but a little high when compared with CMYK results. **The colors orange and green continue to present the best values, while the blue shades are the lowest**.

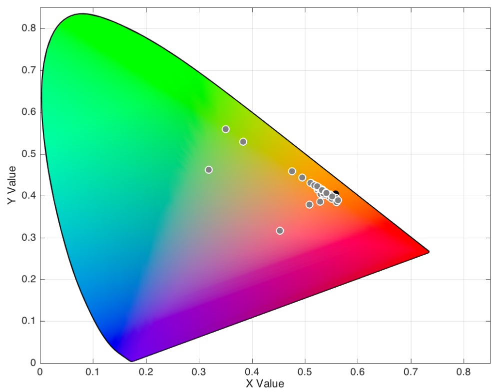

Figure 4.24: Online: Answers for Question 6, from regular users, mixed in RGB Color Model.

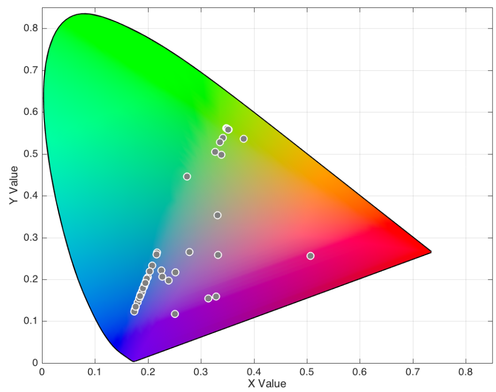

Figure 4.25: Online: Answers for Question 13, from regular users, mixed in RGB Color Model.

When comparing the results from the RGB color model, the majority of users did reveal lack of knowledge in mixing the colors according to an additive color model, as they tended to mix colors according to the CMYK color model. However, this color model has a high degree of compatibility with every other model, excepting CMYK: performing a Wilcoxon Test ($p < 0.05$), we can infer that RGB does not present statistically significant differences with HSV, CIE-L*a*b* and with CIE-L*C*h* in 10 questions, while presenting statistically significant differences with CMYK in 13 questions. Relating to the fact that people either tend to blend colors in an additive or subtractive way, we can compare the results from this color model with CMYK model and state that **users tend to formulate subtractive mental models of color blending**. However, **there is room for further investigation, to fully understand if users are influenced by additive color models or subtractive ones**.

Figure 4.24 represents the results of Question 6, which had the shortest distances to the pre-calculated RGB blend, and Figure 4.25 show the results for Question 13, the question with wider distances. The diagram of Figure 4.26 contains the three top and bottom-valued questions, disposed on top of an interval $[0; 0.5]$ of differences.

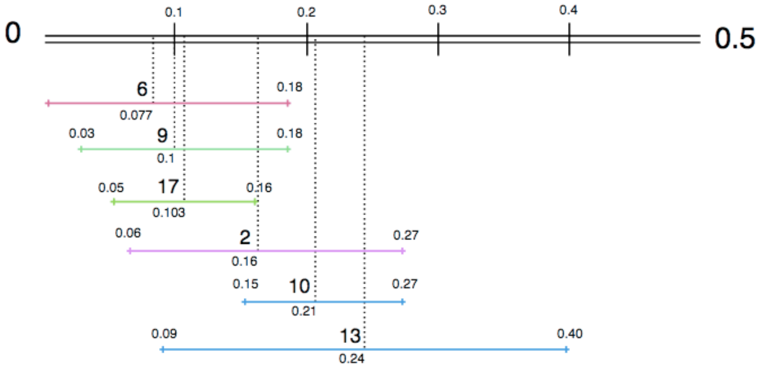

Figure 4.26: Best and Worst Questions, according to RGB Color Model.

CIE-L*a*b* Color Model Blendings This color model has results very similar to CMYK and RGB, since its descriptive statistics have comparable values to this model. The three questions which have shorter distances are number number six (given orange, expected red and yellow), seventeen (given a green, expected cyan and blue) and number nine (given a shade of green, expected green and cyan), which are exactly the same as before. The mean values distances for this questions were $\overline{x}_6 = 0.0509$, $\overline{x}_{17} = 0.1130$ and $\overline{x}_9 = 0.1142$.

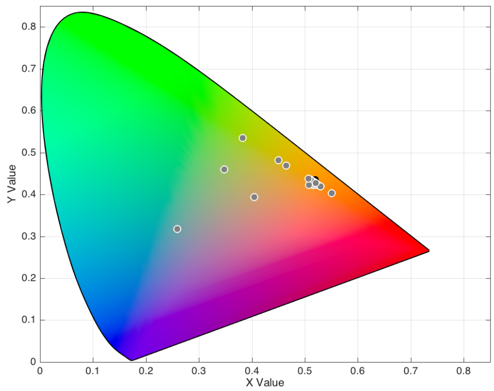

Figure 4.27: Laboratory: Answers for Question 6, from regular users, mixed in CIE-L*a*b* Color Model.

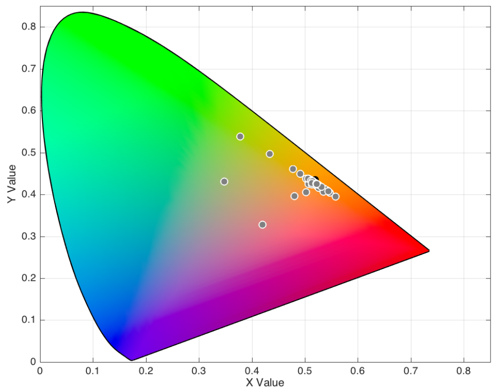

Figure 4.28: Online: Answers for Question 6, from regular users, mixed in CIE-L*a*b* Color Model.

Considering the questions which generate the worst results are number twelve (given a tone of green, expected green and yellow), number ten (given a shade of blue, expected green and magenta) and number thirteen (given a shade of blue, expected blue and cyan), with correspondent mean values $\overline{x}_{12} = 0.1743$, $\overline{x}_{10} = 0.2107$ and $\overline{x}_{13} = 0.2450$. Comparing them with the CIE-L*C*h* Color Model (which is currently the worst-valued color model), we can check that these values are (similar to RGB and HSV) nearer to the later's worst results, but still high when compared with CMYK results (so far, the best-valued color model). **The colors orange and green proved, once again, that they are capable of producing the best values, while the blue shades provided the lowest again**.

When comparing the results from the CIE-L*a*b* color model, we detected that this model has significant differences with all other color models: performing a Wilcoxon Test ($p < 0.05$), we can infer that CIE-L*a*b* does present statistically significant differences with HSV, CMYK and with CIE-L*C*h* in only nine questions, while presenting no statistically significant differences with RGB in ten questions. Since the CIE-L*a*b* conveys the entire set of perceived by the human eye, it **explains why the results associated with this color model are so close to others which yield the best results**. Figure 4.27 represents the laboratory results of Question 6, which not only had the best mean value to the pre-calculated RGB blend, but also its best mean value across all color models, and Figure 4.28 shows the results for the same question, but the online results which confirm the laboratory ones. The diagram of Figure 4.29 contains the three top and bottom-valued questions, disposed on top of an interval $[0; 0.5]$ of differences.

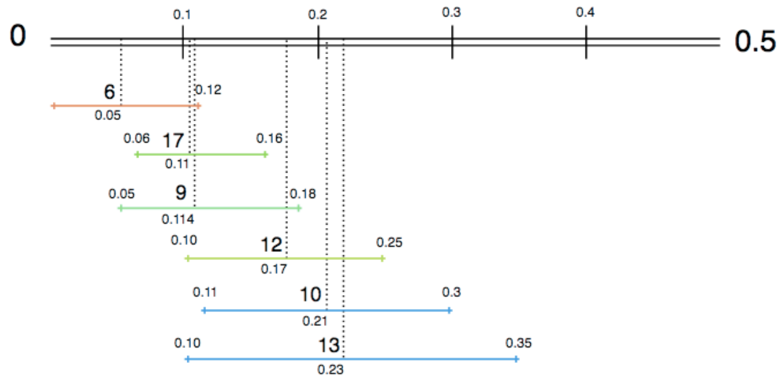

Figure 4.29: Best and Worst Questions, according to CIE-L*a*b* Color Model.

Color Blending Expectation

Besides asking our users to indicate us the two primitives which composed a color blending of two colors, we intended to go further: **comprehend if more than detecting two colors of a mixture, a user is capable of mentally blend two given colors and indicate us its results**.

Therefore, we reverted the previously analyzed seventeen questions, giving the two primitives of the blending to the user, offering at the same time a color slider which contained discretized pre-calculated values (which were nothing more than all the results of all questions, blended accordingly to all color models). Contrary to what was done previously, **we did not blend the answer given by the user, since the colors presented were already blended**, missing only to calculate the distance of answers to the ideal ones: the results for these questions are expressed on Table 4.25, with cells shaded in green which represent the best value for each one of questions.

As seen on the table, the results are roughly similar to the ones found on Table 4.23, which depicts the mean values for the results of questions which presented the result of a given mixture. However, there are some differences which we would like to comment.

- Cyan - As referred before, mistakenly the cyan color was not presented to the user in order to indicate a blending-basis which could create such color. However, we can analyze the results of this question present on Table 4.26; as seen, the color model which has the closest ideal result is the CIE-L*a*b* ($\overline{x}_{lab} = 0.11$, $\overline{x}_{online} = 0.10$), opposite to CIE-L*C*h* which has the farthest response, according to users' responses in both laboratory and online environment. Curiously, HSV, RGB and CMYK all have very close results from each other. Further studies may focus

Question ID	Presented Colors		Reference Pair	Laboratory Environment					Online Environment				
	C1	C2		HSV	CIE-L*C*h*	CMYK	RGB	CIE-L*a*b*	HSV	CIE-L*C*h*	CMYK	RGB	CIE-L*a*b*
Question 18	Red	Green	(77, 93, 14)	0.14	0.14	**0.11**	0.15	0.14	0.12	0.12	**0.08**	0.12	0.11
Question 19	Red	Blue	(59, 28, 97)	**0.16**	0.23	0.17	**0.16**	0.19	**0.13**	0.24	0.19	0.14	0.19
Question 20	Green	Blue	(54, 79, 107)	0.13	0.17	0.14	0.13	**0.11**	0.12	0.17	0.13	0.12	**0.10**
Question 21	Red	Cyan	(45, 76, 12) (27, 12, 95)	0.28 0.23	0.26	0.13	**0.12**	0.17	0.29 0.23	0.26	0.13	**0.12**	0.16
Question 22	Red	Magenta	(45, 23, 22)	**0.18**	0.20	0.25	0.21	0.20	**0.14**	0.16	0.20	0.17	0.16
Question 23	Red	Yellow	(49, 37, 5)	**0.16**	**0.16**	**0.16**	0.18	**0.16**	0.09	**0.08**	**0.08**	0.10	**0.08**
Question 24	Cyan	Magenta	(18, 7, 95)	0.27	0.12	**0.08**	0.12	**0.08**	0.28	0.11	**0.09**	0.13	**0.09**
Question 25	Magenta	Yellow	(41, 21, 2)	0.27	0.18	0.12	0.13	**0.10**	0.21	0.12	0.07	0.07	**0.06**
Question 26	Green	Cyan	(40, 73, 32)	0.12	**0.10**	**0.10**	0.14	0.11	0.12	**0.11**	0.12	0.14	0.12
Question 27	Green	Magenta	(26, 23, 98) (49, 37, 5)	0.20 0.24	0.27	**0.12**	**0.12**	0.13	0.27 0.18	0.21	0.10	0.10	**0.09**
Question 28	Green	Yellow	(45, 76, 12)	0.19	0.17	**0.15**	0.18	0.17	0.17	0.15	**0.12**	0.16	0.15
Question 29	Blue	Cyan	(26, 23, 98)	0.13	**0.07**	0.09	0.13	0.09	0.13	**0.07**	0.09	0.13	0.09
Question 30	Blue	Magenta	(27, 12, 95)	0.16	**0.12**	0.13	0.15	**0.12**	0.18	**0.13**	**0.13**	0.17	0.13
Question 31	Blue	Yellow	(40, 73, 32) (45, 23, 22)	0.11 0.24	0.29	**0.10**	**0.10**	0.14	**0.10** 0.26	0.29	0.12	0.13	0.17
Question 32	Cyan	Yellow	(36, 72, 13)	0.16	0.09	0.09	0.09	**0.07**	0.15	0.08	0.07	0.08	**0.05**

Table 4.25: Results: Distances of Results according to each Color Model, for questions 18 to 32, with the distance from itself to the ideal pre-calculated answer.

Question ID	Presented Colors		Reference Pair	Possible Results									
	C1	C2		HSV		CIE-L*C*h		CMYK		RGB		CIE-L*a*b*	
20	Green	Blue	(54, 79, 107)	(54, 79, 107)		(32, 34, 100)		(12, 17, 23)		(12, 17, 23)		(26, 28, 40)	
				$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
Distance to Objective - Laboratory				0.13	0.06	0.17	0.09	0.14	0.08	0.13	0.06	**0.11**	0.05
Distance to Objective - Online				0.12	0.06	0.17	0.08	0.13	0.07	0.12	0.06	**0.10**	0.06

Table 4.26: Question 20, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

in unraveling which is, in fact, the best color model, since **there is insufficient information to affirm which color model originates the closest distances, according to users' expectations**. Figure 4.30 depicts the answers given by the online users: although this user sample has the lowest distance to ideal answer, it is possible to observe that data is a bit scattered across the chromaticity diagram.

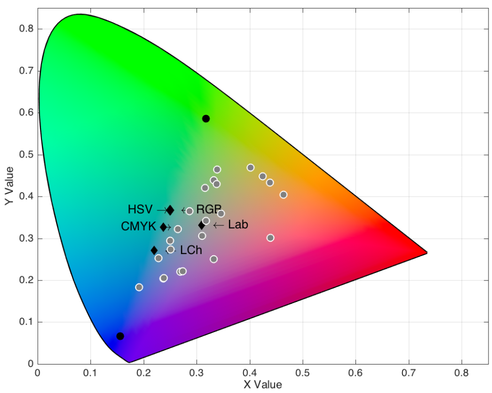

Figure 4.30: Online: Answers for Question 20, from regular users.

- Distances - Comparing the mean distances obtained previously on Table 4.24 which were obtained by questions one to seventeen, the distances generated by the answers from questions eighteen to thirty-two are a bit higher on the HSV Color Model. However, this could be due to the fact **we have only presented discretized colors as options, and did not leave any wiggle-room for the user to indicate other colors which he thought it could be more appropriate**; moreover, this could be related to **users tended to explore and choose answers from other color models, instead of HSV possible answers**. Even so, the values are similar to the previous studied, being only the HSV and CMYK mean values higher than previously ($\overline{x}_{HSV} = 0.18$, $\overline{x}_{CMYK} = 0.13$). Blending Cyan and Yellow to produce green is an example of a question which had one a higher value ($\overline{x}_{Green=Cyan+Yellow} = 0.11$) when asked the user to indicate the blending-basis with subsequential blending in CIE-L*a*b* (question seventeen), and when it was asked the result of the same blending (question nineteen), it provided one of the lowest mean distance values when compared to the ideal CIE-L*a*b* response ($\overline{x}_{Cyan+Yellow=Green} = 0.05$); this example if pictured in Figures 4.31 and 4.32.

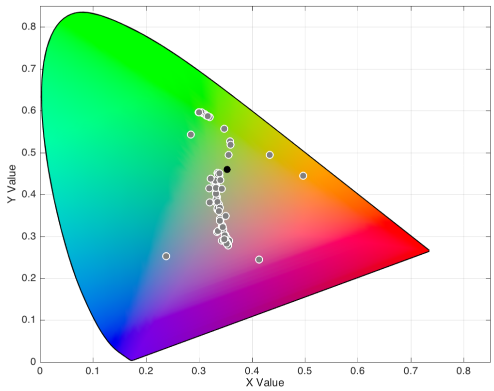

Figure 4.31: Online: Answers for Question 17, from regular users, mixed in CIE-L*a*b* Color Model.

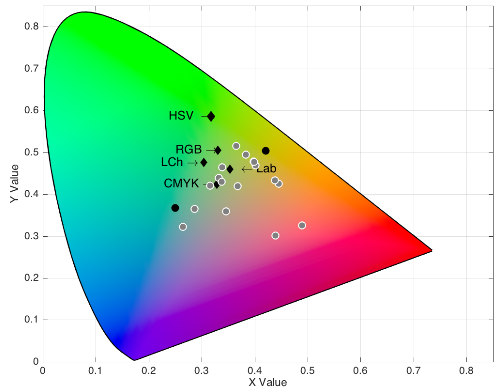

Figure 4.32: Online: Answers for Question 32, from regular users.

- Orange Blending - Comparing the results from all questions, we end up concluding that the question which constantly had best results among all color models was the blending of red and yellow to create orange. However, as it is observable, these results represent much higher distances to the ideal answer in any color model, than when given the user the resulting color of the blending. This fact could accuse that **it is harder for the users to detect the result of a color blend, when two blending basis are given, than when the resulting color is given**, even for the orange color blending which produced very good results in the previous analysis. This could be related to the lack of descriptive power which the color slider supplied the user, which was referred before. This conclusion is corroborated by the online users which, although generating lower mean values than the laboratory ones, are coherent with being higher than the ones previously studied.

- Blue Blending - Recalling the previous analysis, the results for mixtures which resulted in a blue shade all had the worst results among all questions, across all color models. *Per contra*, the results for questions which present a blending basis for creating a blue color had presented much closer distances than before. For example, question twenty-four presented Cyan and Magenta seeking a Blue answer: when the users were asked to indicate the basis (question seven), it generated higher standard deviations which are illustrated in Table 4.23. However, as seen on Table 4.27, the results substantially improve when the users were asked to formulate the result of such blending. This could potentially suggest that **according to the users' expectation, it is easier for them to indicate the result of a blue mixture when the blending-basis is given, than when the user is asked to create the blending-basis according to their mental color model**.

Blending Basis		Resulting Color	Results									
			HSV		CIE-L*C*h		CMYK		RGB		CIE-L*a*b*	
Cyan	Magenta	(18, 7, 95)	Laboratory ($\overline{x}$)	Online ($\overline{x}$)	Laboratory ($\overline{x}$)	Online ($\overline{x}$)	Laboratory ($\overline{x}$)	Online ($\overline{x}$)	Laboratory ($\overline{x}$)	Online ($\overline{x}$)	Laboratory ($\overline{x}$)	Online ($\overline{x}$)
Given Result, Expected Basis			**0.16**	**0.13**	0.23	0.18	0.10	0.11	0.15	0.17	0.17	0.22
Given Basis, Expected Result			0.27	0.28	**0.12**	**0.11**	**0.08**	**0.09**	**0.12**	**0.13**	**0.08**	**0.09**

Table 4.27: Results of Blending Cyan and Magenta, obtaining Blue.

- Color Models Analysis - There were some changes concerning the descriptive statistics associated with distances values from each color model, specially when discovering which models yielded the best and worst results. To help us establish the comparisons between color models, we created an auxiliary Table (4.28) which contains the values. Contrary to questions in which the user was asked to indicate the blending basis, **the color model which has the worst results is the HSV Color Model** ($\overline{x}_{HSV} = 0.18$) while the one which has **the shortest mean distance value continues to be CMYK, along with CIE-L*a*b*** ($\overline{x} = 0.13$). Though, when processing the values for the whole statistics, RGB Color Model turns out to be the one which contains the best results: this not only is confirmed by the online users' data, but also is contrary to the results from the first analysis which dictated that the best color model was CMYK. This is particularly interesting, since it reveals that **when the users are asked to combine colors after a resulting one is given, they tend to blend according to a subtractive color model (*e.g.* CMYK); but, when the blending-basis is given, the users are likely to mix the colors according to an additive color model (*e.g. RGB*)**.

On its turn, CIE-L*C*h* continues to reveal itself as the worst-valued Color Model, having the highest standard deviation ($s = 0.07$), the highest range of distances ($range = 0.22$) and the highest variance of values ($s^2 = 0.005$), across both study environments.

Descriptive Statistics	Laboratory Environment					Online Environment				
	HSV	CIE-L*C*h*	CMYK	RGB	CIE-L*a*b*	HSV	CIE-L*C*h*	CMYK	RGB	CIE-L*a*b*
Mean ($\overline{x}$)	**0.18**	0.17	**0.13**	0.14	**0.13**	**0.17**	0.15	**0.11**	0.13	0.12
Std-Dev (s)	0.06	**0.07**	0.04	**0.03**	0.04	**0.07**	**0.07**	0.04	**0.03**	0.04
Maximum Value	0.28	0.29	0.25	0.21	0.20	0.29	0.29	0.20	0.17	0.19
Minimum Value	0.11	0.07	0.08	0.09	0.07	0.09	0.07	0.07	0.07	0.05
Range	0.17	**0.22**	0.17	**0.12**	0.13	0.20	**0.22**	0.13	**0.10**	0.14
Variance (s^2)	0.003	**0.005**	0.002	**0.001**	0.002	0.004	**0.005**	0.002	**0.001**	0.002

Table 4.28: Condensed Statistics for Distances to Ideal Results, according to each Color Model, for questions 18 to 32. In Green/Red shade, the best/worst result for each descriptive statistic.

Therefore, we can summarize the results in one table, which ranks the color models *per* color blending, dividing it between two strands: based on the values that represent questions in which the user was asked to indicate the blending-basis, and based on the values that represent questions in which the user was asked to point out the correct blending result when given two colors. These results are presented in Table 4.29. The color models were ranked according to the descriptive statistics' values generated by each question, weighted with the results from the laboratory environment and the validation from the online users: for each question, we started by searching for the lowest mean value from the laboratory values, then comparing it with its correspondent from the online environment to validate it; if there was any tie between values from the same environment, **the untie would be done by evaluating the standard deviations** and it would be chosen the color model which had the lowest value. If the untie was not possible, then **we did not have enough information to state which color model was better than another**.

For example, we performed the following evaluation for **question four** values:

1. On the laboratory environment, the color model which had the lowest mean value was **CMYK** ($\overline{x}_{CMYK} = 0.10$); the same for the online environment ($\overline{x}_{CMYK} = 0.11$).

2. On the laboratory environment, the color model which had the second lowest mean value was **HSV** ($\overline{x}_{HSV} = 0.12$); the same for the online environment ($\overline{x}_{HSV} = 0.11$).

3. On the laboratory environment, the color model which had the third lowest mean value was **RGB** ($\overline{x}_{RGB} = 0.19$); the same for the online environment ($\overline{x}_{RGB} = 0.21$).

4. Lastly, there were two color models which had the highest mean values, on the laboratory environment: **CIE-L*a*b* and CIE-L*C*h*** ($\overline{x} = 0.20$); however, the value from the online environment was lower for CIE-L*C*h* Color Model ($\overline{x}_{LCh} = 0.22$), than the CIE-L*a*b*.

5. Therefore, we conclude that the color models can be ranked in the following order, according to their descriptive statistics: **CMYK, HSV, RGB, CIE-L*C*h* and CIE-L*a*b***.

Marked in **bold**, on Table 4.29, are the color models which we have concluded to yield the best results, according to each type of question asked: **CMYK** when given the result and asked for the blending-basis, and **CMYK and RGB** for the questions whose blending-basis was given and the result was asked. For the blends of Magenta-Yellow and Blue-Cyan, we did not found conclusive results, as referred before: for the first one, it was not possible to concretely state which color model was the best, since all color models yielded similar closer distances; for the later blending, it was possible to concretely affirm which color model was the best or worst, since all color models provided higher distances, very similar between each other.

Blending Basis		Blending Result	Given the Result, Asked for Basis					Given the Basis, Asked for Result				
C1	C2	C3	#1	#2	#3	#4	#5	#1	#2	#3	#4	#5
Red	Green	(77, 93, 14)	**CMYK**	CIE-L*a*b*	RGB	HSV	CIE-L*C*h*	**CMYK**	CIE-L*a*b*	HSV	**RGB**	CIE-L*C*h*
Red	Blue	(59, 28, 97)	**CMYK**	CIE-L*a*b*	CIE-L*C*h*	RGB	HSV	HSV	**RGB**	**CMYK**	CIE-L*a*b*	CIE-L*C*h*
Green	Blue	(54, 79, 107)	-					CIE-L*a*b*	**HSV, RGB**		**CMYK**	CIE-L*C*h*
Red	Cyan	(45, 76, 12)	**CMYK**	HSV	RGB	CIE-L*a*b*	CIE-L*C*h*	**RGB**	**CMYK**	CIE-L*a*b*	HSV	CIE-L*C*h*
		(27, 12, 95)	**CMYK**	HSV	RGB	CIE-L*C*h*	CIE-L*a*b*					
Red	Magenta	(45, 23, 22)	**CMYK**	CIE-L*C*h*, CIE-L*a*b*, RGB			HSV	HSV	CIE-L*C*h*, CIE-L*a*b*		**RGB**	**CMYK**
Red	Yellow	(49, 37, 5)	CIE-L*a*b*	**CMYK, HSV, RGB**			CIE-L*C*h*	**CMYK, CIE-L*C*h*, CIE-L*a*b***			HSV	**RGB**
Cyan	Magenta	(18, 7, 95)	**CMYK**	RGB	HSV	CIE-L*a*b*	CIE-L*C*h*	**CMYK, CIE-L*a*b***		CIE-L*C*h*	**RGB**	HSV
Magenta	Yellow	(41, 21, 2)	Inconclusive Results					CIE-L*a*b*	**CMYK**	**RGB**	CIE-L*C*h*	HSV
Green	Cyan	(40, 73, 32)	**CMYK**	RGB	CIE-L*a*b*	HSV	CIE-L*C*h*	CIE-L*C*h*	**CMYK**	CIE-L*a*b*	HSV	**RGB**
Green	Magenta	(26, 23, 98)	**CMYK**	RGB	CIE-L*a*b*	HSV	CIE-L*C*h*	**RGB**	**CMYK**	CIE-L*a*b*	HSV	CIE-L*C*h*
		(49, 37, 5)	HSV	**CMYK**	CIE-L*C*h*	CIE-L*a*b*	RGB					
Green	Yellow	(45, 76, 12)	HSV	**CMYK**	RGB	CIE-L*a*b*	CIE-L*C*h*	**CMYK**	CIE-L*C*h*, CIE-L*a*b*		**RGB**	HSV
Blue	Cyan	(26, 23, 98)	Inconclusive Results					CIE-L*C*h*	CIE-L*a*b*	**CMYK**	**HSV, RGB**	
Blue	Magenta	(27, 12, 95)	**CMYK**	HSV	RGB	CIE-L*a*b*	CIE-L*C*h*	CIE-L*C*h*, CIE-L*a*b*		**CMYK**	**RGB**	HSV
Blue	Yellow	(40, 73, 32)	**CMYK**	HSV	RGB	CIE-L*a*b*	CIE-L*C*h*	**CMYK**	**RGB**	HSV	CIE-L*a*b*	CIE-L*C*h*
		(45, 23, 22)	**CMYK**	CIE-L*a*b*	RGB	HSV	CIE-L*C*h*					
Cyan	Yellow	(36, 72, 13)	**CMYK**	HSV	RGB	CIE-L*a*b*	CIE-L*C*h*	CIE-L*a*b*	**CMYK**	CIE-L*C*h*	**RGB**	HSV

Table 4.29: Colors Models, ranked from best to worst, associated to every color blending studied.

4.4.3 Color Mixtures and Color Naming

Being the color models covered in the extensive previous analysis, we are left to analyze and break down each color mixture, understanding if there is a particular color blending which has an added level of difficulty. As stated on Section 3.1, it is also interesting to study if the users have a particular choice to order the colors when demonstrating their answers, given its implications on how to draft Information Visualization Artifacts, such as sliders, scales or color blends to convey information. This subSection will be composed on two main groups: on the first one, we will focus our attention on the color blendings which are **based on primary colors, to generate other primary colors** to comprehend if the users can detect and formulate primary color blendings; the second group of this subSection will contain a **brief investigation about the difficulty found when blending colors**, focusing our attention not only on each question, but also on providing a general perception of how the study went, regarding the facility of unveiling color mixtures.

We also performed a color analysis by comparing the colors given by our users, with the ones obtained with the XKCD's Color Bins referred on the *Data Processing* Section (4.3.2) of this document. This way, we can make sense out of the values, giving them meaning and necessary categorization. This is going to be useful when analyzing the proximity of values.

Primary Colors

Among all the questions proponed to the user, there were of six of them which presented as the result of a color mixture, either one of the following primary colors: **Red, Green, Blue, Cyan, Magenta,** or **Yellow**. These results are the primitives from one additive color model (RGB) and one subtractive color model (CMYK): what we intend to know is if the user is capable of creating color blendings which result in these colors; since these color models are complementary, the user must reveal knowledge of mixing colors according to these two models, while creating blendings with colors from the opposite color model. These questions are refreshed again on Table 4.30.

Question ID	Blending Basis		Blending Result	Possible Results				
	C1	C2		HSV	CIE-L*C*h	CMYK	RGB	CIE-L*a*b*
8, 25	Magenta	Yellow	Red	(41, 21, 2)	(48, 32, 12)	(53, 38, 25)	(53, 38, 25)	(62, 51, 43)
17, 32	Cyan	Yellow	Green	(36, 72, 13)	(49, 77, 47)	(49, 78, 33)	(49, 78, 33)	(66, 87, 46)
7, 24	Cyan	Magenta	Blue	(18, 7, 95)	(39, 49, 102)	(35, 27, 98)	(35, 27, 98)	(56, 50, 101)
20	Green	Blue	Cyan	(54, 79, 107)	(32, 34, 100)	(12, 17, 23)	(12, 17, 23)	(26, 28, 40)
2, 19	Red	Blue	Magenta	(59, 28, 97)	(44, 22, 22)	(13, 6, 21)	(13, 6, 21)	(29, 14, 25)
1, 18	Red	Green	Yellow	(77, 93, 14)	(42, 42, 6)	(17, 20, 3)	(17, 20, 3)	(39, 42, 6)

Table 4.30: Color Blends based on Primary Colors, which result in other Primary Colors.

As analyzed before, according to the users' responses and expectations, these questions show a fair degree of concordance when blending the mixture-basis, since they all tend tend to present better results when blended according to a CMYK Color Model. However, we have found an interesting behavior from our users when answering these questions: some users indicated the resulting color on both the reference pairs (*e.g.* Red was presented, and the users indicated twice the color Red in their answers); we will briefly analyze the values for each of the blendings referred on Table 4.30, as it has already been analyzed before.

Magenta + Yellow = Red In this question, it was expected that users indicate a mixing of Magenta and Yellow to blend in a result of Red. These colors are primitives from the CMYK Color Model which, when blended, generate a color from the complementary color model, the RGB. However, the laboratory users did focus their answers on **orange, green, blue and even red hue**; moreover, these results were similar among the online users and did not demonstrated a consensual answer pair.
Additionally, five laboratory users (from thirteen which indicated a pair of two answers - 38.46% of the users) and forty-two online users (from sixty-two - 67.74% of the users) indicated, at least, one time the red color as an answer. We can even run some descriptive statistics on top of the distance values between the given answers and the expected Magenta-Yellow Pair ($\overline{x} = 0.49$, $s = 0.25$) and observe that these evidences lead us to believe that **the users do not know how to create a red color based on other primary colors**.
When analyzing question number twenty-five, in which we ask the user which color is the result of blending Magenta and Yellow, we conclude that **the results are, also, scattered a bit**, which leads us to reinforce the statement above. **There is also no observable tendency to begin the color blending with a particular shade of a color**. Figures 4.33 and 4.34 show us the answers given by the online users in, respectively, question eight and twenty-five.
Finally, since we have produced the mapping between given values and color bins, we can perform a qualitative analysis of each answer pair's colors names while comparing it to the expected ones. The expected pair was Magenta-Yellow: among 62 answers from the online users to question 8, **we conclude that the colors Magenta and Yellow were among the least indicated ones**, being Magenta indicated four times and five times. The most repeated color was Red, being indicated more than 70 times: there were 31 answer-pairs (50%) which contained the color Red twice! When given by the user,

the Magenta was combined with Green and Red, while Yellow was combined with Red, Green and Blue; however, the specific pair Magenta-Yellow was never indicated.

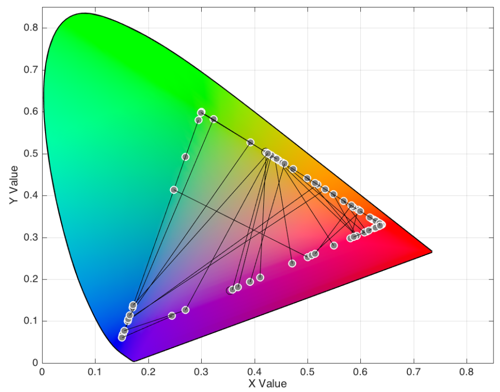

Figure 4.33: Online: Answers for Question 8, from regular users.

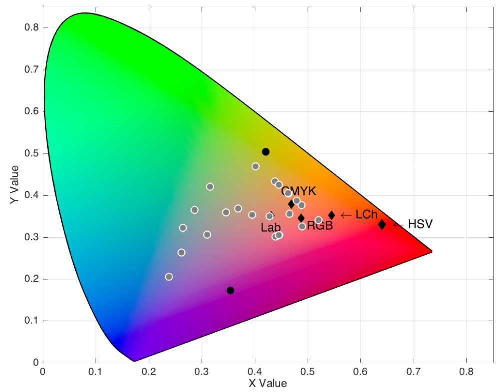

Figure 4.34: Online: Answers for Question 25, from regular users.

Cyan + Yellow = Green Regarding this, it was expected that users indicate a mixing of Cyan and Yellow to blend in a result of Green. Similarly to the previous blend, these colors are primitives from the CMYK Color Model that, when blended, generate a color from the RGB Color Model. Curiously, both the laboratory and online users provided their answers on similar pairs, comprised between **blue shades and yellow ones**; the most repeated color pairs were, in fact, Blue shades combined with tones of green and yellow, as observable on Figure 4.35.

Additionally, only two laboratory users (from twenty-three which indicated a pair of two answers - 8.70% of the users) and six online users (from seventy-one - 8.45% of the users) indicated an answer pair which did not even nearly approximate to the desired hues. Running some descriptive statistics on top of the distance values between the given answers and the expected Magenta-Yellow Pair ($\overline{x} = 0.40$, $s = 0.21$) did reveal longer distances also; however, since the majority of answers are near a cyan hue tending to a blue one, we consider these answers as valid ones. These evidences lead us to believe that **the users do present knowledge on how to create a green color based on other primary colors, such as cyan/blue and yellow**.

When analyzing question number thirty-two, in which we ask the user which color is the result of blending Cyan and Yellow, we conclude that **the results, as previously happened with other primary blends, are a bit scattered**. As before, **there is no observable tendency to begin the color blending with a particular shade of a color**. Figures 4.36 and4.36 show us the answers given by the online users in, respectively, question seventeen and thirty-two.

We can perform a qualitative analysis of each answer pair's colors names while comparing it to the expected ones. The expected pair was Cyan and Yellow: among 71 answers from the online users to question 17, **we conclude that the color Yellow was among the least indicated ones**; however, users have diverged a little when indicating the cyan color, since **the users have answered with colors varying between Blue, Navy-Blue, Sky-Blue, Light-Blue and Teal**, with frequencies of 37, 11, 3, 1 and 1 respectively, while Cyan was only referred 4 times. Though, users have referenced a lot more times the Green color, which is the presented one: 77 times to be more precise, with **53 answer-pairs formed with a Blue shade and Green** (75% of the totality of pairs) and 10 pairs which contained the Green color twice. If analyzed, the CIE Chromaticity Diagram in Figure 4.35 consolidates this idea, revealing the dispersion of blue derived colors' usage, but a slight concentration of answers in the neighborhood of

Green and Yellow. Regarding the latter color, it was combined 4 times with blue shades which is another indicator that **users presented strong Blue-Green/Yellow blending capabilities**.

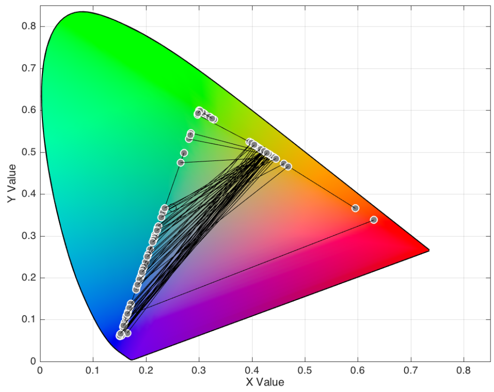

Figure 4.35: Online: Answers for Question 17, from regular users.

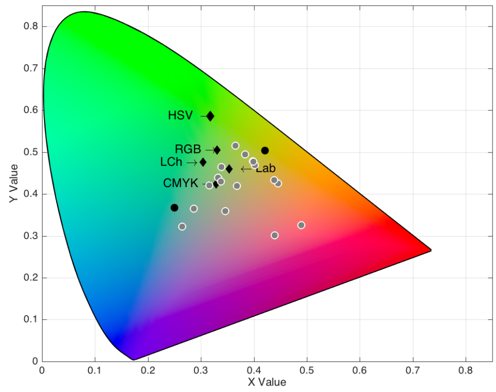

Figure 4.36: Online: Answers for Question 32, from regular users.

Cyan + Magenta = Blue In this question, it was expected that users indicate a mixing of Cyan and Magenta to blend in a result of Blue; these colors are primitives from the CMYK Color Model. Both the laboratory and online users provided their answers on similar pairs, comprised between **blue shades, yellow ones, magenta's and pink, and some greens and reds**. There was also an interesting aggregation of results on both environment, near the green and yellow shades.
However, as seen on Figures 4.37 and 4.38 there exists a tendency of users indicating answers very close to the given color (Blue Hue). This could reveal an **inability of detecting a blue blending basis**, which could be related to the (lack of) descriptive power among blue colors, previously referred.
5 Running some descriptive statistics on top of the distance values between the given answers and the expected Cyan-Magenta Pair ($\overline{x} = 0.45$, $s = 0.11$) reveals the same high mean distance value, but a lower than previous standard deviation of results. Due to the fact that the users indicated some answers in the magenta zone of colors and some blue/cyan hues, we could state that **although there is no strong evidence to verify this color blending, the users show a mild ability to blend cyan and magenta, providing a blue color**.
When analyzing question number twenty-four, in which we ask the user which color is the result of blending Cyan and Magenta, we conclude that **the results, as previously happened with other primary blends, are a bit scattered**. As before, **there is no observable tendency to begin the color blending with a particular shade of a color**.

Performing a qualitative analysis of each answer pair's colors names while comparing it to the expected pair was Cyan-Magenta, we obtain the following results: among 76 answers from the online users to question 7, **we conclude that the colors Cyan and Magenta were among the least indicated ones**; instead, the users have indicated related shades to these colors, like Blue (97 times, consistent with the previously analyzed blending using Cyan), Pink (10 times), Purple and Red with smaller repetitions. However, it is interesting to observe that the users consistently answered a Green shade 26 times, as observed in the CIE Chromaticity Diagram in Figure 4.38. The users answered 35 times with an answer pair of Blue-Blue (46% of users sample), 11 times Green-Green (15%), and 8 pairs with Blue shaded colors and Magenta derived ones (11%). This is a question with poorer results, which may bye derived from aforementioned problems related to human blue color perception.

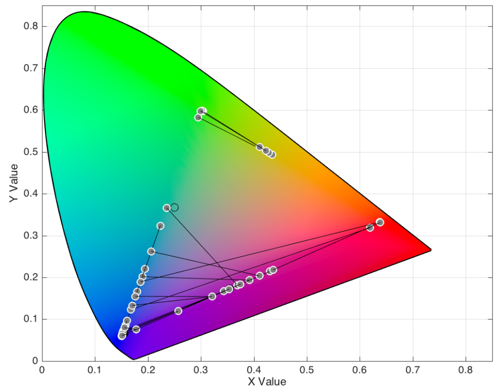

Figure 4.37: Laboratory: Answers for Question 7, from regular users.

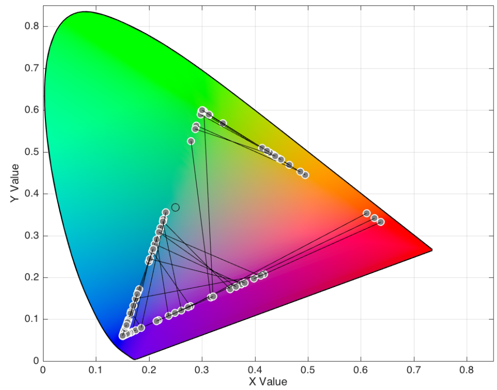

Figure 4.38: Online: Answers for Question 7, from regular users.

Green + Blue = Cyan As said before, this color blending was only conducted only in one way. In this question, it was expected that users indicate the result of mixing Green and Blue: Cyan; these colors are primitives from the RGB Color Model. Both the laboratory and online users provided similar results, with an aggregation of them on the blue and cyan hues on both environment, and also in the orange hue (for unknown reasons).

Running some descriptive statistics on top of the distance values between the given answer and the expected Cyan Color ($\overline{x} = 0.13$, $s = 0.06$) reveals some proximity to the reference pair, and a lower standard deviation of results. Ideally, the results should be compared with the other type of question asked; since there is no question to compare and based on previous analyzed results, we can affirm that **there are mild evidences that users can detect a Green-Blue blend to provide a Cyan color**. However, **further studies should deepen this question and determine if this affirmation could be corroborated**.

Red + Blue = Magenta In this question, it was expected that users indicate a mixing of Red and Blue to mix in a result of Magenta. Both the laboratory and online users provided their answers on similar pairs, comprised between **blue shades, yellow ones, magenta's and pink, and some greens and reds**. There was also an interesting aggregation of results on both environment, **along the line which unites Blue and Red**, with some scattering among the cyan and teal colors.

However, as seen on Figure 4.39 there exists a tendency of users indicating answers very close to the given color (Blue Hue). This scattering of results could be related to the **blue blending detection problems**, previously referred.

Running some descriptive statistics on top of the distance values between the given answers and the expected Red-Blue Pair ($\overline{x} = 0.53$, $s = 0.36$) reveals the highest mean distance value so far, and also a deviation of results higher than before. the users indicated some scattered answers in the blue zone of the chromaticity diagram: answers include Light-Blue, Sky-Blue, Navy-Blue and Cyan, besides the typical Blue; on the other hand, the users have indicated spared answers in the Magenta zone: Dark-Purple, Pink, Magenta and Red. This shattering of data is consistent with the deviation of values obtained: we could state that **the users demonstrated some basic conception of blending red and blue to obtain magenta**. However, **the users have indicated more detailed colors, contrary to other color blends previously evaluated**, which may have implications on the level of detail that the displaying of color should have.

Analyzing question number nineteen, in which we ask the user which color is the result of blending Red and Blue, we conclude that **the results, as previously happened with other primary blends, are a bit scattered**, leaving no plausible conclusion to formulate. In this blending, **there is an observable tendency to begin the color blending with the red color**: on a frequency of twenty-four laboratory users, six of them (25%) indicated a Red value as the first color, leaving the second color to indicate a more detailed color; the same happens when analyzing sixty-three online users, where 33% of them indicated a Red color as the first value. Relating the late dataset, it was also interesting to observe that 33% of the users left the Blue color as a second answer. This could be due to **magenta being a relatively close color to a red hue**, leading the user to indicate firstly the color which he recalls the most, that happens to be red.

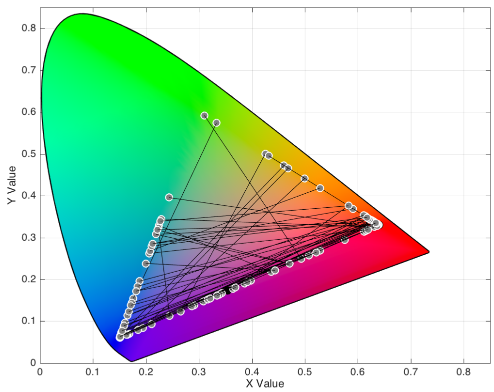

Figure 4.39: Online: Answers for Question 2, from regular users.

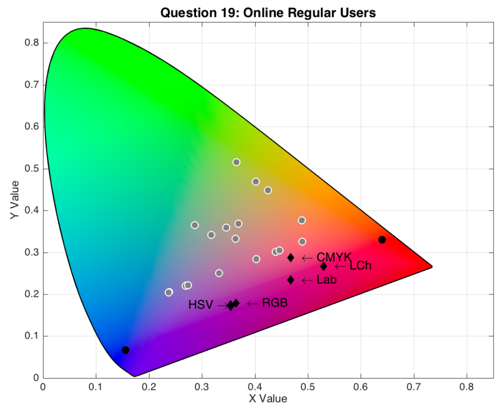

Figure 4.40: Online: Answers for Question 19, from regular users.

Red + Green = Yellow Lastly, it was expected that users indicate a mixing of Red and Green to mix in a result of Yellow. Both the laboratory and online users provided their answers on similar pairs, comprised between **blue shades, yellow ones, red and cyan**. There was also an interesting aggregation of results on both environment, **along the line which unites Blue and Green, and Green and Red**, with a heavy concentration of results near the yellow shades, as seen on Figure 4.41.

The answer-pairs which contained Yellow presented this colors slightly shaded to orange, which could signify that **the users provided an orangish-yellow with another color in order to blend the first one to the ideal Yellow Hue**.

Running some descriptive statistics on top of the distance ($\overline{x} = 0.41$, $s = 0.22$) reveals roughly the same mean distance and standard deviation as before. In this question, the users revealed a balmy concordance amongst themselves, according to color bins labeling: the users centralized their answers on Blue, Navy-Blue, Orange, Red, Yellow and Green. We could state that **the users demonstrated some basic conception of blending red and green to obtain yellow**, but further studies should focus on understating which influence is the blue color exercising on the user's mental model, since it was a constant result among study environments.

Analyzing question number eighteen, in which we ask the user which color is the result of blending Red and Green, we conclude that **the results show an approximation to the ideal color result, but a scattering over orange and yellow colors**. In this blending, **there is a slight observable tendency to begin the color blending with a red color**, as depicted in online users' dataset (20% of fifty-three users) started the mixture with a Red Color. However, this is not a relevant result by itself: it is indeed consistent with the result collect from the previous mixture.

Performing a qualitative analysis of each answer pair's colors names while comparing it to the expected pair was Red-Green, we obtain the following results: among 53 answers from the online users to question 1, **we conclude that the colors Red and Green were among the most indicated ones**; the reference pair was indicated 15 times (28.3%), while the Green-Green pair also referred in other questions appears 25 repetitions (47%): this latter pair may be referred by the user as an "escape answer", when he does not knwo what to blend. This could be observed in Figure 4.41.

instead, the users have indicated related shades to these colors, like Blue (97 times, consistent with the previously analyzed blending using Cyan), Pink (10 times), Purple and Red with smaller repetitions. However, it is interesting to observe that the users consistently answered a Green shade 26 times, as observed in the CIE Chromaticity Diagram in Figure 4.38. The users answered 35 times with an answer pair of Blue-Blue (46% of users sample), 11 times Green-Green (15%), and 8 pairs with Blue shaded colors and Magenta derived ones (11%). This is a question with poorer results, which may bye derived from aforementioned problems related to human blue color perception.

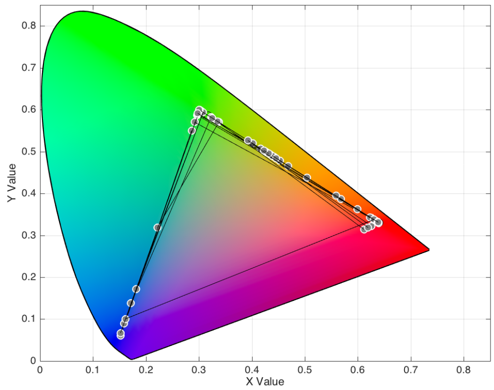

Figure 4.41: Online: Answers for Question 1, from regular users.

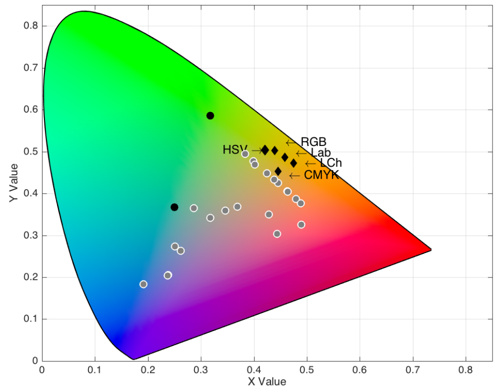

Figure 4.42: Online: Answers for Question 18, from regular users.

Color Blending Effort

We have collected from the users the easiness of blending two shades of colors, when concluding each answer. This easiness is reflected in an numerical scale, ranged from one to five, being one the hardest level of effort, and five the easiest level of effort. The results were gathered and analyzed, and are resumed in Table 4.31, where we associate to each color blending the effort degrees the users found when answering the two types of questions discussed before. For better appreciation, the table presents in green shaded cells the color blendings which have a Mo value of Difficulty level equal to five, and shaded in red the color blendings which present the lowest Mo value (two).

As seen on the table, the results are in agreement with the ones collected and concluded before: the **blending of Red-Green resulting in Yellow**, **blending of Red-Yellow and Green-Magenta, both resulting in Orange** and the **blending of Cyan-Yellow resulting in Green** were the mixtures which, according to the users' answers, had the lowest effort of blending, consequently the highest rating of easiness; particularly for the mixture of Red and Yellow, resulting in Orange, it provides the best results in both question types. Contrary, the questions which had the lowest results were almost always the ones in which the user was inquired about the result of given blending basis.

Nevertheless, it is interesting to observe that the results for the generality of questions encircle the rating of 2 and 3 in the interval $[1;5]$, which could indicate that **apart from the obvious color blendings which proved to yield the best results, all the other blendings show nor an easy or hard level of effort to mix the basis**. These results are confirmed by the online responses, by running a Friedman

Blending Basis		Blending Result	Given the Result, Asked for Basis						Given the Basis, Asked for the Result					
			Laboratory			Online			Laboratory			Online		
C1	C2	C3	Mean ($\overline{x}$)	Std-Dev (s)	Mode (Mo)	Mean ($\overline{x}$)	Std-Dev (s)	Mode (Mo)	Mean ($\overline{x}$)	Std-Dev (s)	Mode (Mo)	Mean ($\overline{x}$)	Std-Dev (s)	Mode (Mo)
Red	Green	(77, 93, 14)	3.58	1.21	**5**	3.72	1.45	**5**	3.10	1.05	3	2.67	1.20	3
Red	Blue	(59, 28, 97)	3.13	1.41	3	3.17	1.26	3	3.54	0.96	3	3.57	1.23	**5**
Green	Blue	(54, 79, 107)	-						3.32	1.22	**2**	3.10	1.25	3
Red	Cyan	(45, 76, 12)	3.95	1.09	4	3.80	1.05	3	3.14	1.06	3	2.97	1.11	3
		(27, 12, 95)	3.28	0.97	3	3.49	1.15	4						
Red	Magenta	(45, 23, 22)	3.22	0.81	3	3.13	1.19	3	3.14	0.89	3	3.10	1.08	3
Red	Yellow	(49, 37, 5)	3.86	1.08	4	4.08	1.00	**5**	3.26	1.06	3	4.10	1.05	**5**
Cyan	Magenta	(18, 7, 95)	3.5	1.19	3	3.32	1.59	**5**	3.04	1.23	**2**	2.90	1.23	3
Magenta	Yellow	(41, 21, 2)	2.92	1.22	**2**	2.62	1.50	**5**	2.70	0.82	3	2.75	1.24	**2**
Green	Cyan	(40, 73, 32)	3.42	0.90	3	3.26	1.10	4	3.50	1.20	4	2.94	1.19	**2**
Green	Magenta	(26, 23, 98)	3.43	1.16	3	3.50	1.35	3	2.68	1.16	3	2.25	1.17	**2**
		(49, 37, 5)	4.17	0.887	**5**	2.06	1.035	**5**						
Green	Yellow	(45, 76, 12)	3.71	0.96	3	3.67	1.07	4	3.18	1.19	3	3.31	1.24	4
Blue	Cyan	(26, 23, 98)	3.63	1.26	**5**	3.53	1.12	4	3.48	0.99	3	3.41	1.12	3
Blue	Magenta	(27, 12, 95)	3.50	0.8	3	3.49	1.13	3	3.25	1.11	4	3.19	1.16	3
Blue	Yellow	(40, 73, 32)	3.75	0.86	4	3.58	1.14	4	3.57	1.03	4	3.61	1.12	3
		(45, 23, 22)	3.47	0.83	3	3.27	1.17	3						
Cyan	Yellow	(36, 72, 13)	3.96	0.98	4	3.90	1.16	**5**	3.36	0.95	4	3.54	1.17	3

Table 4.31: Color Blending Effort, according to users' answers.

Test which indicates us that there are no statistically significant differences ($p < 0.05$) when comparing the results from the laboratory environment, with the online results.

During the analysis and data cleaning, we have found a substantial portion of data which reflected the users' answers which contained only one component, when it was expected a pair of two. These answers were separated from the original dataset and we have decided not to eliminate these answers, since they could provide useful inputs to our analysis, discerning if the users did not indicate a second color for the sake of convenience, or because they did not know what to blend, or simply to blend the given answer with a white color, lightning it down to a lighter color. The blendings which had more solitary answer were **Green-Magenta, producing a Blue shade** (63 entries), **Red-Green, producing Yellow** (60 entries) and **Blue-Yellow, producing a Pink shade** (56 entries); the ones which had less were **Red-Yellow, producing a Orange shade** (26 entries), **Green-Yellow, producing a Lime-Green color** (24 entries) and **Blue-Magenta, producing a Purple shade** (20 entries). Analyzing these answers, we conclude that the option of **indicating only one color is not due to knowing just one primitive of the blending**, since a barely set of users indicated correctly one primitive. However, there was a tendency for users to indicate colors which were near ($distance < 0.1$) the resulting color (already presented): this could indicate that **the users either left an empty color as a whitening one, along with a darker shade than the result, or they indicated the same color as the result, according to their expectation and color perception**. Since it is not possible for us to judge this information based on these results only, it would be ideal if further studies could deepen this matter. Figures 4.43 and 4.44 all represent the set of answer-pairs with one white component, for questions one, ten and fifteen, respectively.

4.4.4 Demographic Results

To conclude the analysis of our dataset, we performed a set of statistic tests to realize if there is some kind of connection between the demographic information of our users and the answers given by them, for example a relation between the answers given by the male and female users, or even if the younger users interpret the color blendings differently from the older ones. As referred in the beginning of this Section, we have separated the users among some demographic groups: regarding the age division we have created six groups (users aged below 20 years, aged between 20 and 29, between 30 and 39, 40 and 49, 50 and 59, and above 60 years), and for the gender we have divided the dataset according to female, male and other gendered users. These groups were, then, iterated by question, performing a

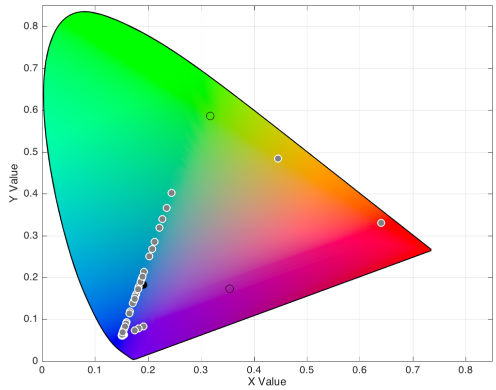

Figure 4.43: Answer-pairs with one white component, from Question 10.

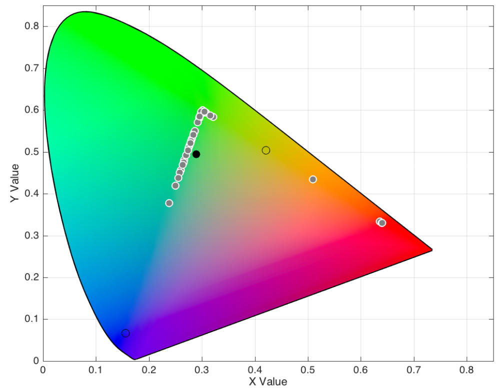

Figure 4.44: Answer-pairs with one white component, from Question 15.

Spearman's Rank-Order Correlation test between the ages and genders, with the answers; since the amount of data available is quite high, this test would dictate which questions would be subject of further analysis in this Section.

Additionally, it would be interesting to perform a crossed analysis between genders and age groups: however, the size of the dataset does not provide the amount of information needed to corroborate such analysis. Hereupon, we are going to divide the analysis of these demographic groups on the next subSections, starting by analyzing the results for the age groups highlighting the questions which manifested statistically significant correlations, followed by the evaluation of the gender groups. To end this Section, we will perform an additional informal evaluation of the results collected from color vision deficient users.

Age Groups

Recalling Table 4.3, present of Section 4.4.1, we have collected a total of 259 users, being 38 users aged below 20 years, 162 users aged between 20 and 29 years, 20 users aged between 30 and 39 years, 19 users aged between 40 and 49 years, 12 users aged between 50 and 59 years and 8 users aged above 60 years. When analyzing the results from all 32 questions, for each of these age groups, with Spearman's Correlation test we conclude that there are no statistically significant correlations ($\rho < 0.05$) when comparing the distances from answers blended in each color model (HSV, CIE-L*C*h*, CMYK, RGB and CIE-L*a*b*) with the age from the users, for the majority of questions except for a small subset: from all 32 questions asked, seven of them presented weak, positive and negative correlation between the age values and the calculated distances, which have statistically significant correlation values ($\rho < 0.05$).

These questions are number six ($r_s(6) = 0.22$, $\rho = 0.013$), seven ($r_s(7) = -0.18$, $\rho = 0.032$), eight ($r_s(8) = -0.21$, $\rho = 0.015$), nine ($r_s(9) = 0.19$, $\rho = 0.029$), nineteen ($r_s(19) = 0.19, \rho = 0.028$), twenty-five ($r_s(25) = 0.18$, $\rho = 0.034$) and, finally, question thirty-one ($r_s(31) = -0.19$, $\rho = 0.031$).

To better comprehend the differences between age groups on the aforementioned questions, we have executed a Wilcoxon Signed-rank Test ($p < 0.05$) in order to detect significant differences which exist, between results for each color model, by age group. The test reveals that:

1. There are statistically significant differences ($p = 0.021$) on question six (expected Red-Yellow, presented Orange color), when blending the answers in HSV Color Model, between the users aged below 20 years and the ones aged between 40 and 49 years;

2. There are statistically significant differences ($p = 0.042$) on question seven (expected Cyan-Magenta, presented Blue color), when blending the answers in RGB Color Model, between the users aged between 40 and 49 and the ones aged between 50 and 59 years. Also, there are significant differences ($p = 0.043$) when blending the same answers according to the CIE-L*a*b* Color Model, between the same age groups.

3. There are statistically significant differences on question 25 (expected Red, presented Magenta-Yellow pair), when measuring the distances from the answers to the ideal blending, according to CIE-L*a*b* Color Model, between the following age groups:

   - The users aged below 20 years and the ones aged between 20 and 29 years ($p = 0.038$);
   - The users aged between 20 and 29 years and the ones aged between 30 and 39 years ($p = 0.002$);
   - The users aged between 20 and 29 years and the ones aged between 40 and 49 years ($p = 0.028$).

4. There are statistically significant differences on question 31 (expected Green or a shade of Magenta, presented Blue-Yellow pair), when measuring the distances from the answers according to the following Color Models:

   - HSV, for the distances to the shade of Magenta, between the users aged below 20 years and the ones aged between 40 and 49 years ($p = 0.008$);
   - CMYK, between the users aged below 20 years and the ones aged between 40 and 49 years ($p = 0.042$);
   - CIE-L*a*b*, between the users aged below 20 years and the ones aged between 40 and 49 years ($p = 0.032$).

These values indicate us that the age group which was always present in each difference, for the selected questions, was **the users aged between 40 and 49 years**. However, **there is insufficient information for us to confirm that this age group presents much different values from the others**, since these questions present a minority of the sample. It is also **not possible to affirm that there are significant differences between all age groups**, because there are more questions which do not present any difference *per* color model and the analyzed differences include only a subset of all age groups. Hence, **we did not found relevant differences between age groups**; further studies should explore this research topic.

Figures 4.45 and 4.46 reflects the statistically significant difference when blending the answers from the orange blending (question six), in HSV Color Model, between the users aged below 20 years and the ones aged between 40 and 49 years.

Gender Groups

Recalling Table 4.3, we have collected a total of 259 users, being 105 Female Users, 152 Male Users and 2 Other Gender Users. Similarly to what was done before, we analyzed the results from all 32 questions, for each of these gender groups, with Spearman's Correlation test: we have conclude that there are no statistically significant correlations ($\rho < 0.05$) when comparing the distances from answers blended in each color model with users' gender, for the majority of questions. Notwithstanding, eight of them presented weak, positive and negative correlation between the gender types and the calculated distances, which have statistically significant correlation values ($\rho < 0.05$).

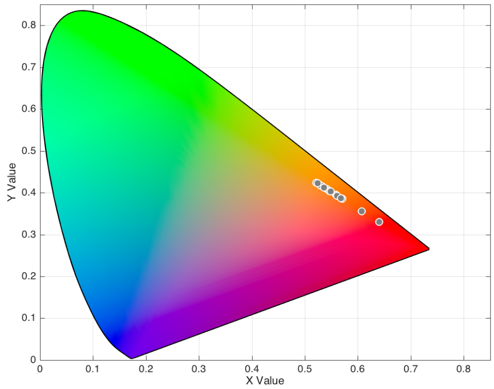

Figure 4.45: Demographic Results, from Question 6, from users aged below 20 years, blended according to HSV Color Model.

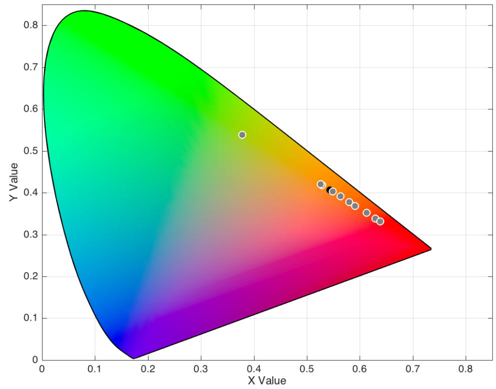

Figure 4.46: Demographic Results, from Question 6, for answers given by users aged between 40 and 49 years, blended according to HSV Color Model.

These questions are number six ($r_s(6) = 0.17$, $\rho = 0.049$), nine ($r_s(9) = -0.17$, $\rho = 0.043$), eleven ($r_s(11) = 0.182$, $\rho = 0.038$), fifteen ($r_s(15) = 0.22$, $\rho = 0.012$), sixteen ($r_s(16) = -0.19, \rho = 0.024$), seventeen ($r_s(17) = 0.18$, $\rho = 0.037$), question twenty-two ($r_s(22) = 0.19$, $\rho = 0.024$) and, finally, question number thirty ($r_s(30) = 0.19$, $\rho = 0.025$).

Equally to age groups' analysis, we have executed a Wilcoxon Signed-rank Test ($p < 0.05$) in order to detect significant differences which exist, between results for each color model, by gender group. The test reveals that:

1. There are statistically significant differences ($p = 0.027$) on question nine (expected Green-Cyan, presented a tone of Green), when blending the answers in CMYK Color Model, between the Male and Female users. Among 64 cases, 38 of them presented wider distances for Female users, while 20 were higher for Male users;

2. There are statistically significant differences ($p = 0.035$) on question eleven (expected Green-Magenta, presented Orange color), when blending the answers in HSV Color Model, between the Male and Female users. Among 61 cases, 23 of them presented wider distances for Female users, while 33 were higher for Male users;

3. There are statistically significant differences ($p = 0.048$) on question 15 (expected Blue-Yellow, presented a tone of Green), when blending the answers in CIE-L*C*h* Color Model, between the Male and Female users. Among 63 cases, 25 of them presented wider distances for Female users, while 33 were higher for Male users;

4. There are statistically significant differences on question 16 (expected Blue-Yellow, presented a shade of Magenta) between the Male and Female users, when blending their answers according to the following color models:

    - RGB, with 63 cases, 39 of them presented wider distances for Female users, while 17 were higher for Male users ($p = 0.009$);

    - CIE-L*a*b*, with 63 cases, 38 of them presented wider distances for Female users, while 19 were higher for Male users ($p = 0.009$);

5. There are statistically significant differences ($p = 0.011$) on question 17 (expected Cyan-Yellow, presented Green color), when blending the answers in CIE-L*a*b* Color Model, between the Male

and Female users. Among 63 cases, 38 of them presented wider distances for Female users, while 19 were higher for Male users;

6. There are statistically significant differences on question 23 (expected Orange, presented Red-Yellow pair), when measuring the distances from the answers according to the following Color Models:

   - HSV, with 69 cases, 19 of them presented wider distances for Female users, while 38 were higher for Male users ($p = 0.005$);
   - CMYK, with 69 cases, 16 of them presented wider distances for Female users, while 33 were higher for Male users ($p = 0.006$);
   - RGB, with 69 cases, 120 of them presented wider distances for Female users, while 39 were higher for Male users ($p = 0.008$);

These values potentiate a conclusion which was discussed in the theoretical background of this master thesis: there is a mild difference between the results from the Female gendered users, and the Male ones. It is not an absolute difference, since **not every question had presented significant differences between gender groups**; it is **not possible to formulate a conclusion about which gender generates the wider or closer distances to the ideal answer (according to each Model)**, since there is no visible pattern about this subject. There were no significant differences between female or male users, and the *other* gendered users: this could due to the lack of a significant user sample relating the later gender.

This leads us to conclude that there is, in fact, space for a theory on **the existence of a difference in color perception by the female users, when compared with the male users**: this difference is observable in our study results, but not substantial to formulate any a formal research conclusion. Figures 4.47 and 4.48 represents the statistically significant difference when blending the answers from the shade of magenta blending (question 16), in RGB Color Model, between the Female and Male users: in these Figures, **we can distinguish an eventual lack of color descriptive power concerning Male users** - whose answers are conveying to the grey center of the chromaticity diagram (the black dot on the Figure) - contrasting with the Female one, whose answers show a regular disposition along the edge which unites the Magenta and Red colors.

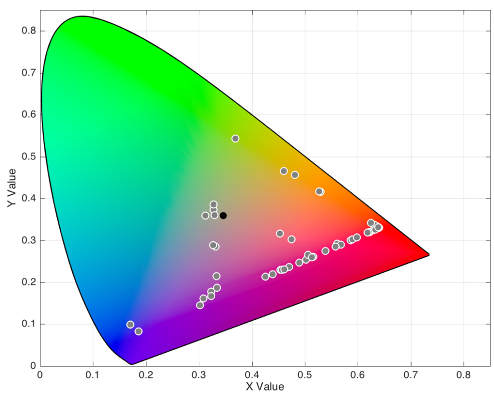

Figure 4.47: Demographic Results, from Question 16, from female users, blended according to RGB Color Model.

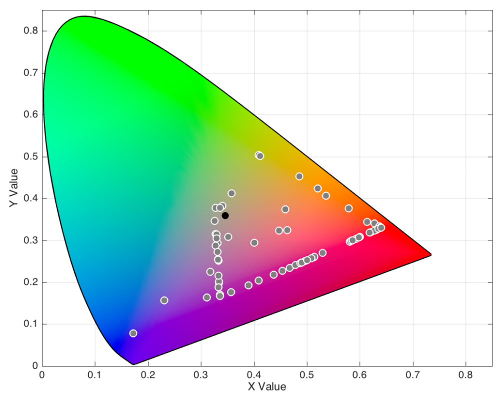

Figure 4.48: Demographic Results, from Question 16, from male users, blended according to RGB Color Model.

Color Vision Deficient Users Group

Based on the criteria defined on Section 3.3, we have analyzed the collected user sample and verified if there was any user which had any type of color vision deficiency. This filtering of users was accomplished via the data collected on the *Color Vision Deficiencies Test Phase*. We had one laboratory user which we have determined to have ***Deuteranopia*, a Red-Green deficiency** and two online users which have ***Deuteranopia and Protanopia***, each one. Since there is not enough information and data sample to perform a statistic analysis and we did not know which colors to expect, according to each color vision deficiency when blending the answers, we performed a qualitative analysis. Though, in this Section, we give examples of some questions which presented colors that could not be correctly visualized by each color vision deficiency.

Magenta + Yellow = Red In this color blending (question number eight), it was asked the users to indicate a Magenta-Yellow pair to mix into a Red color. While the non-color vision deficient users (therefore, simply called *regular users*) have indicated a myriad of possible answer pairs waging between green, blue, yellow and magenta, the color vision deficient (therefore, simply called *daltonic users*) gave answer-pairs very close to the resulting color; this case can be observe on Figures 4.49 and 4.50. This could be caused due to the fact that the Red color, for both types of deficiencies in Red-Green cones, the users received a Yellow stimulus, instead of a Red one (recall Figure 2.3, of Section 2.1.2).

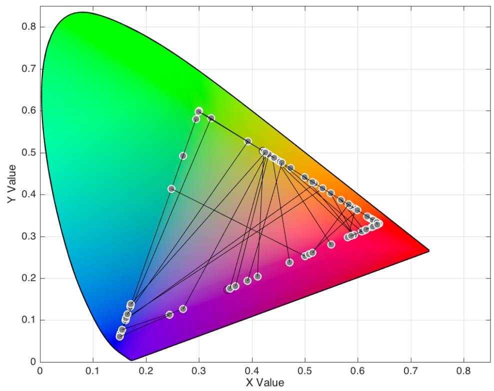

Figure 4.49: Online: Answers for Question 8, from regular users.

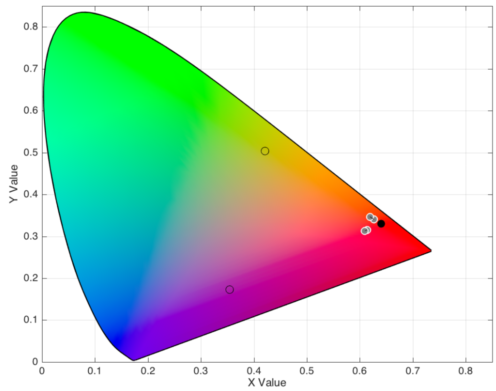

Figure 4.50: Online: Answers for Question 8, from daltonic users.

Cyan + Yellow = Green On the other hand, when we presented one of the blending which collected the best results from all (question 17), the users answered in a similar fashion from the regular users. It was asked the users to indicate a Cyan-Yellow pair to mix into a Green color, and the three daltonic users from both study environment have answered with similar answer-pairs. The laboratory user answered with a Green-Green pair, while the online users answered with a Yellow-Cyan one; this could have many reasons to happen, since these color vision deficiencies transform the Green presented color onto a Yellow shade, but preserves the Blue color as it is, and the yellow color is a very common color to perceive among these deficiencies.

We could make the following analysis: the laboratory user either mixed Yellow-Yellow (adjusted to its color vision deficiency) because he didn't realize the blending-basis, or simply because for him, the yellow color cannot be decomposed onto two primitive colors; respecting the online users, they could have provided this pair since they know for fact to which regular color the color they see correspond to, or because they see a darker shade of yellow (presented) and wanted to indicate a blending basis of Yellow and a darker color like Blue, to darken the mixture. Figures 4.51 and 4.52 help us supporting this explanation.

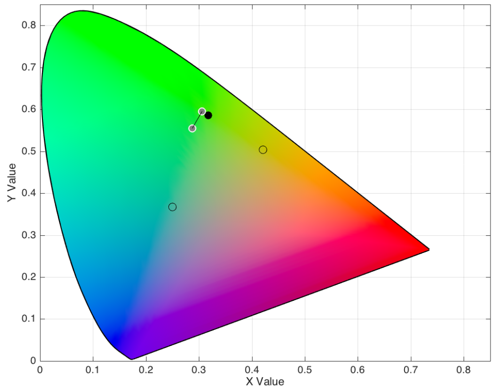

Figure 4.51: Laboratory: Answers for Question 17, from daltonic users.

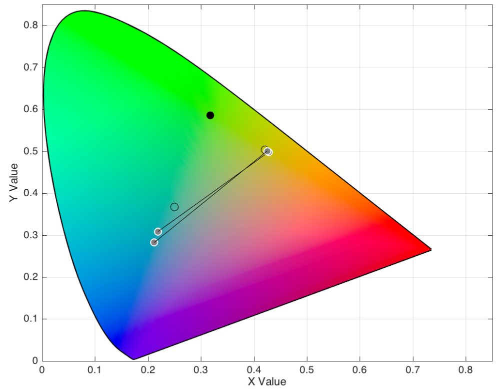

Figure 4.52: Online: Answers for Question 17, from daltonic users.

This is a **purely informal analysis**, since it does not provide any type of statistics and does not produce any type of research conclusion: in order to obtain factual conclusions about this investigation subject, it should be developed an entire user study with daltonic users, providing the necessary amount of data to be correctly analyzed.

4.5 Discussion

The goal of this color study was to: **study a way to present color information which does not influence color perception**, **understand if there is any mental organization of color** and **study the influence of discrete and continuous color scales** on user's answers. Additionally, it was relevant to understand which color model stood as the best to blend colors which are more similar to users' expectation. This user study was developed in two different conditions: in a **Laboratory Environment**, which allowed us to calibrate ans control the entire study conditions, and in a **Online Environment**, which allowed us to broadcast our study to a larger set of users.

We have defined a set of questions which we wanted to answer to, as follows: **Q1:** Which Color Model meets best the users' expectations, when blending two colors?, **Q2:** Is there evidence of a spatial arrangement of colors, when users are indicating possible color mixtures' results?, and **Q3:** Are there evidences from differences across demographic groups, such as the age or gender?. We have performed a statistical analysis of the processed data obtained from the user study: the main data which was analyzed was the one obtained in the laboratory environment, being the online data only the corroboration of the main data. We have started by drafting a profile from the users which we have obtained the data from: our user sample is composed by **259 users**, being 105 Females, 152 Males and a minority of 2 Other gendered users, **171 of these** have a High-Degree of Education and **215 users** have Portuguese Nationality.

In order to study which color model yields the best results, we have interpolated each answer-pair given by the users according to each color model in study: HSV, CIE-L*C*h*, CMYK, RGB and CIE-L*a*b*. These interpolations were performed on the subset of questions comprised between number 1 and 17, which represent the questions in which the result of a given mixture was given, and the user had to answer the question by indicating the answer-pair which he thought it would fit the ideal blending-basis. We have observed that **the color blending which constantly yielded the best results across all color models is the mixing of Red-Yellow, to achieve Orange**, while the mixture which provided the worst results when evaluating the distance from the user's answers and the ideal answers, is **the blending of Green-Magenta, resulting in a Blue shade**: these results are consistent with the ones collected by Gama and Gonçalves [GG14c] before, which concluded that the success rates were higher for blending pairs like Red-Yellow, and worst for pairs which correspond to a wider angle in a Hue circle. For instance, **blending Cyan and Yellow, to obtain Green** had very good results, generating the lowest values for evaluated descriptive statistics across each every color model ($\overline{x}$, s, s^2). These results are, also, **consistent with the fact that the human color perception is conditioned by the amount of Cones present in our eyes** since the users have more descriptive power for colors near the green zone of the spectrum, due to the fact that the eye has substantially more green sensitive cones than blue ones, indicating that minimum variations within Blue colors could not be detected.

When analyzing the answers by Color Model, we can observe that **the HSV Color Model, along with CMYK and RGB, is the one which presents the lowest standard deviation of distances** between the results from the online environment, while **the Color Model which presented the lowest mean value for distances was the CMYK Color Model**. The RGB, HSV and CIE-L*a*b* Color Models all generate values very similar to each other, so **further studies should focus on discerning which color model is better than others, between HSV, RGB and CIE-L*a*b***, since there were no relevant differences among them.

On the other hand, the CIE-L*C*h* Color Model is the one which typically provided the worst results across all color blendings, therefore being **the one which least resembles the users' expectations when blending colors**. The CMYK Color Model is, by far, the one which presents the best results for most of the descriptive statistics, being corroborated by the results from the online environment: the distances from the given answers when blended according to the CMYK Color Model, presented consistently the lowest values across all questions. In fact, the questions which yielded better results are majorly related to primitives of the CMYK color model; this success could be related to the fact that people tend to formulate mental models of color based on ink mixing in childhood [GC04], mostly associating it to Red, Yellow, Blue (RYB) and CMYK Color Models without even knowing it: **These results indicate that CMYK is a highly compatible color model with the users expectations**. For these reasons, we can answer question **Q1**, stating that **the color model which most resembles the user's expectation, when blending two colors according to a given result, is the CMYK Color Model**. Since CMYK is an additive color model, it is safe to say that <u>the type of color models which most resembles the user's expectation, when blending two colors according to a given result, is a subtractive color model</u>.

It is also interesting to observe that the users are able to blend primary colors (Red, Green, Blue, Cyan, Magenta and Yellow) using other primary colors as the blending-basis: however, the results obtained for **Blue and Cyan are consistent with the ones obtained previously**: there is no strong evidence that the users can produce Blue (or blue-derived) color blendings. In opposition, when **creating Green, Magenta and Yellow**, the users revealed some basic conception of blending their basis, with more emphasis on the process of creating Magenta: users have indicated more detailed shades of Red to create the color mixture, contrary to other color blends evaluated, which may have implications on the level of detail that the displaying of color should have. This leads us to answer question **Q2**: **for color blendings which involve the Red color there is, in fact, evidence that the users sort the colors when indicating the blending-basis, revealing some mental color organization**: in the latter case of the Magenta blending, users may have indicated first the Red shades, since it is a color that is more similar to Magenta (the resulting one) and users may have used it to start the mixture, just like when using paint colors.

Besides asking our users to indicate us the two primitives which composed a color blending of two colors, we intended to go further: comprehend if more than detecting two colors of a mixture, a user is capable of mentally blend two given colors and indicate us its results. Therefore, we reverted the way blendings were presented, giving the two primitives of the blending to the user, offering at the same time a color slider which contained discretized pre-calculated values (which were nothing more than all the results of all questions, blended accordingly to all color models). The distances for these questions were higher than the previous ones: this could be due to the fact **we have only presented discretized colors as options, and did not leave any wiggle-room for the user to indicate other colors which he thought it could be more appropriate**. For certain colors (*e.g.* the orange blending) the results were equally good, since there are **color blendings which users are more familiar with and, therefore, are more intuitive**.

We have also performed a demographic analysis to ascertain if there was any plausible difference present in our dataset, between demographic groups. We have conducted an analysis *per* age groups (users aged below 20 years, between 20-29, 30-39, 40-49, 50-59 and above 60 years) and gender groups (Female, Male and Other gendered). Regarding the age groups, we have not found relevant differences between age groups, since not every color blending had presented statistically significant differences between the groups; however, from the ones which had presented differences, the users aged between 40 and 49 years were present in every difference detected. Still, **we do not have enough ground truth to support a conclusion about the existence of age differences**.

We cannot say the same thing about gender groups differences: there is a mild difference between the results from the Female gendered users, and the Male ones. It is not an absolute difference, since not every question had presented significant differences between gender groups; also, it is not possible to formulate a conclusion about which gender generates the wider or closer distances to the ideal answer (according to each Model), since there is no visible pattern about this subject. There were no significant differences between female or male users, and the other gendered users: this could due to the lack of a significant user sample relating the later gender. This leads us to conclude that **there is, in fact, space for a theory on the existence of a difference in color perception by the female users, when compared with the male users**: this difference is observable in our study results, but not substantial to formulate any a formal research conclusion.

Finally, we have studied the users' effort in blending colors: the results are in agreement with the ones collected and concluded before, in which the blending of Red-Green resulting in Yellow, blending of Red-Yellow and Green-Magenta, both resulting in Orange and the blending of Cyan-Yellow resulting in Green were the mixtures which, according to the users' answers, had the lowest effort when blending, consequently the highest rating of easiness. It is interesting to observe that the results for the generality of questions encircle the rating of two and three, on a scale from one to five, which could indicate that apart from the obvious color blendings which proved to yield the best results, all **the other blendings show nor an easy or hard level of effort to mix the basis**. Answering question **Q3**, **it is possible to observe that there are evidences of difference between demographic groups, but only between genders**.

4.5.1 Guidelines for the usage of Color Blending

The following list enumerates a set of guidelines which we are able to formulate, based on our user study, about the usage of color blending when sketching visualizations:

1. To maximize the compatibility with the user's expectations, **choose** color blends which present Orange shades based on mixing Red and Yellow.

2. Color blends which present a resulting color of Green are welcomed by the user, since it is easier for him to detect smaller changes on **green shades**, than on blue shades.
3. The Yellow color provides very good results, when blending Red and Yellow. The CMYK Color Model is the one which has the best results, according to user's expectations.
4. To maximize the compatibility with the user's expectations, **avoid** presenting colors which are near Blue shades, since the user's perception does not yield the best results.
5. When using Red shades, the best blending-basis is Red and Magenta. If the resulting color is presented instead of the basis, the color model which is has better results is the CMYK; however, if the blending-basis is presented and the result asked, avoid the CMYK and present the result interpolated according to HSV Color Model.
6. Presenting the resultant color from a given blending, generally, produces better results than asking the user to blend the color according to his mental model of color.
7. The color model which best resembles the user's expectation is a subtractive one, for example **CMYK**. However, do **not** use it to present Blue shades since it yields higher distances to user's expectation.
8. If the usage of CMYK Color Model is not convenient, the usage of HSV, RGB and CIE-L*a*b* produces similar results between each other, but slightly weaker results when compared to CMYK.
9. Avoid using the CIE-L*C*h* Color Model when blending colors according to the user's expectations. Except when asking the result for the following color blendings: Green and Cyan, Blue and Cyan, Blue and Magenta, and Red and Yellow.
10. Consider including the white color in the set of presented colors for the user to work with.

4.5.2 Calibration Resiliency

During the analysis of the dataset, we verified that there was a smaller set of five online users which had presented erratic calibration values. Since these users could provide interesting values to establish a comparison between values gathered on a calibrated, *versus* an uncalibrated study environment, we have kept them in a separate dataset for comparisons. These users, similarly to color vision deficient users, were subject of a qualitative comparison, due to the fact that there is insufficient data to demonstrate significant comparisons.

Since the laboratory users performed the color study inside a controlled and calibrated environment, they are not examined in this analysis. Performing a Friedman Test over the results from calibrated users and uncalibrated users, we concluded that only two questions show statistically significant differences between results: they are question two ($\chi^2 = 24.853$, $p < 0.05$) an question 13 ($\chi^2 = 17.209$, $p < 0.05$). However, when analyzing the chromaticity diagrams from question two, present in Figures 4.53 and 4.54, we end up concluding that **there is no substantial difference between calibrated and uncalibrated results**. Remember that question 2 asked for a answer-pair of Red-Blue to a Magenta color presented.

To consider that a user presented a calibration which was not correct, we based our evaluation on the **Calibration Test Phase** of the study: there is still the chance that, despite the user provided wrong values considering the ones expected, his calibration was in fact correct to carry out the study. Since the majority of questions of this user study revealed no significant difference between calibrations, we can state that **this color study was resilient to changes in calibration values**; however, there is **no relevant research conclusions to elaborate from this subject**.

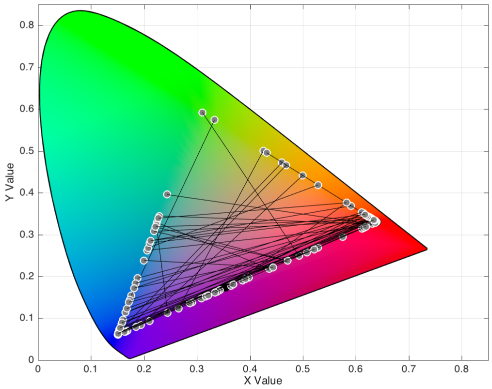

Figure 4.53: Online: Answers for Question 2, from calibrated users.

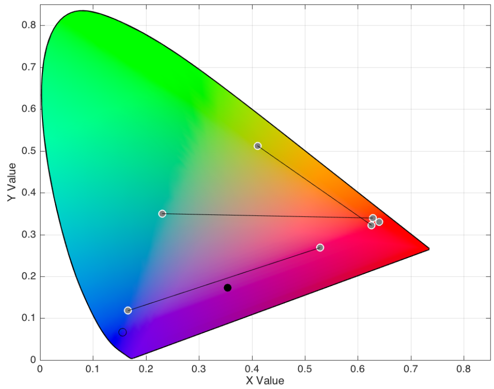

Figure 4.54: Online: Answers for Question 2, from uncalibrated users.

4.5.3 Implications for InfoVis

This research produced a set of useful results which could have some impact in the Information Visualization (InfoVis) Research area. As it is know, conveying data values through marks and channels is typical of an infovis: via geometric shapes, their size, length, motion, or hue; particularly, the latter is an interesting topic, which is to convey information via color. Using one color to transmit the information contained in one variable is straightforward (though discussion may be raised about which is the best color), the not-so-trivial subject about this is when we want to carry more than one variable with different colors: do color blendings effectively work when two colors are mixed and presented to the user?

There are many ways to tackle the blending of colors when presenting two data variables in an infovis: for example, one can attribute a color in its maximum saturation to each variable and simply blend them, presenting to the user the result already digested. However, this raises many questions such as *Which color model should be used to present the color blending result?*, or *Which color blending should be used to provide the best results, as well as creating an appealing visualization?*; one can also ask if *Is there any rule-of-thumb for adding relative quantities of each color?*.

Though this subject may be extended to blendings with more than two colors, we believed that **the more colors involved in a color mixture, the greater the confusion which may happen when trying to interpret the results carried in each color**: this could occur, since the majority of users may not be familiar with the process of mixing colors, as it is not a task conducted out recurrently in a daily basis. If the user is not familiar with the process, this could cause an overhead when he tries to interpret the visualization and, if he cannot interpret it, whatever happens next may lead him to leave the visualization since he may not be able to overcome the inherent learning curve.

It is important to understand what is best to keep the user's focus, while corresponding to his expectations at the same time: is it to present the information visualization already with the colors blended, leaving to the user the task of perceiving the underlying values? Or is it better to give the user the freedom to blend the colors which he feels more comfortable with? We conducted a color study with a sample of users, where we presented a set of colors which resulted from blending pairs of two colors according to five color models (HSV, CMYK, RGB, CIE-L*a*b* and CIE-L*C*h*). The colors were presented in the study interface in agreement with the HSV Color Model, since it was the one which could provide the *tools* of presenting the color as we wanted in the visualization: varying **H**ue, maximum **S**aturation and maximum **V**alue, so we could range the colors we wanted to present inside the range of $[0^o; 360^o]$. It is totally valid to use the HSV Color Model to manipulate the colors presented in a information visualization (typically developed using web technologies), since it provides light colors, shades and greys only by varying the H, S and V primitives.

Though, we have found that **the color model which better corresponds to the user's blending expectation is the CMYK Color Model**: this is notably interesting, since we can relate this result with the known fact that the users created their mental models of color according to infant experiences of paint pigments blending. In fact, the users are much more familiar with blending paint colors, than blending light colors: except for the users which are familiar with RGB Color Model (typically the Computer Science ones), the majority of users formulated their mental model of color in accordance with subtractive color models.

CMYK, then, proves to be the color model which most likely the users would follow if they had to decompose a color presented. There are some artifacts which could support the color blending analysis, like Legends, but it would be better for the user if the information visualization is self-contained and he did not depend on analyzing other artifacts. This is what a visualization Designer, ultimately, wants: to create mappings which are natural for the user to follow and compose. We have discovered that the **color blendings which are more inherent to the user are the ones which generate Green, Orange or Yellow**, being **Blue derived shades the least detectable color blendings**: again, this is consistent with the known fact that the human perception of color is deeply affected by the number of color-detecting cells in the eye, which have higher frequencies for **M**edium and **L**arge Wavelength Sensitive Cones (Green-Red color perception), than **S**mall Wavelength Sensitive Cones (Blue color perception).

The creation of any visualization should be supported by a convenient color scale, which should be adapted to the type of data which is trying to convey: if the data we are conveying does need an ordering, then no Hue should be provided since the users will see categories that are not there. On the other hand, it should not be provided any Luminance or Saturation when categories are wanted, because the users will see order that are not there. In our study, we provided a continuous color scale when we asked for the color-pair which originated a given result color, since the underlying values of the slider were simply the Hue angles from the HSV color model; contrary, we have presented a discrete color scale when asked for the result of blending a given blending-basis, since the values of the slider were the pre-calculated results according to each color model. Our user study confirms that **the usage of continuous color scales should be limited to cases in which the user is intended to oscillate the value of a variable and adjust it as he may**, and that **the usage of discrete color scales should be indicated when giving the user tools to blend colors associated to pre-defined containers of information** as Gama and Gonçalves stated [GG14b].

We have gathered a generous amount of data from users which provide only one answer, followed by a white color; these users lead us to conclude that **it would be of major interest to the user to include the white color in a color scale** so he can adjust the percentage of color which he wants to indicate. This would be interesting when providing visualizations in which the user could perceive a relative amount of data associated with a color, for example in a choropleth (*e.g.* Figure 2.21), where the user is presented with the same color but in different shades or tones.

It was also interesting to observe that the users are capable of formulating better the blending-basis when given the result, than formulating the result when given the blending-basis; this could be related to act of creating and imagining the colors which are not given, it may be easier for the user to indicate colors which he knows (which belong to a set of *named-colors*, like Red, Green or Yellow), than to create a product of two colors. For example, **it was easier for the users to indicate that Magenta and Yellow result in a Red shade when given the result, than when the basis was given**. Imagining an information visualization, it is the same as stating that **it is best for the user to perceive an already blended color and process it according to its mental model of color**, than to give a white screen and ask the user to create the color blendings.

Additionally, it would be interesting to explore the differences between genders (Female and Male) and adapt the amount of *descriptiveness* visually perceived by the user according to its gender; since it is plausible that there is, in fact, some mild difference between the color descriptive power of man and woman, **an information visualization that could provide such feature would be, besides more enjoyable, more adapted to the descriptive capabilities of each user** and capable of providing better results and less frustration.

Chapter 5

Conclusion

This chapter will conclude the dissertation. It will summarize its major contributions and ramifications and discuss directions for future work.

In this Master thesis, we aimed to understand if color blendings can be detected by the users; but, as we have seen in this document, color has many different scopes which are not trivial. It was important to conceive a scientifically adjusted research, since this topic aggregates so many different areas as psychology, physiology, medicine and computer science at the same time. There are many questions which remain unanswered, about the influence of our cultural background in color perception tasks, how the background of a subject influences its color, how information visualization is influenced by the usage of color blending, among others previously referred in this document. Since this project aims to achieve the Master Degree in Computer Science, we only tackled some of these topics: *understand if color blendings can be detected by the users*, *test if it is better to give the result already mixed, or indicate the blending-basis and the user creates the color mixture*, *to detect if the users follow some kind of mental convention and organize the color when conveying the answers*, and formulate possible implications of color blending usage, in Information Visualization field of research.

These goals only constituted the user study of our project, which aimed to answer three questions: **Q1:** Which Color Model meets best the users' expectations, when blending two colors?, **Q2:** Is there evidence of a spatial arrangement of colors, when users are indicating possible color mixtures' results?, and **Q3:** Are there evidences from differences across demographic groups, such as the age or gender?

We gathered a generous amount of 259 users, which helped us study which color model yielded the best results. We have found that CMYK is model that best resembles the users' expectations, while the orange, green and yellow color-blending results are the ones which generate shorter distances to between the expected colors and the ones indicated by the users. On the other hand, the CIE-L*C*h* Color Model is the one which is farther apart from the users' mental model of color.

It was interesting to observe that there is a mild indicator that it exists a difference between the responses from Female and Male users. However, since our user sample was not complete enough to determine this difference, and not every color blending has presented statistically significant differences between genders, there is no substantial ground-truth to formulate any a formal research conclusion.

We have also formulated a set of guidelines which could be followed when using color blending to convey information, which gathered the conclusions from the all the study results' analysis and summarized it in rule-of-thumbs to follow.

With this Master Thesis, we have set some implications for the Information Visualization field of research, from the Color Model to use when presenting color blendings, to what should be asked the user (either the blending-basis or the result of the blending) in order to maximize the success rate of each visualization, following the color blendings which yield the best results at the same time they are consistent with the human color perception.

The advent of Information Visualization brings the eagerness of showing beautiful information, in most efficient and fastest way possible to attract users: color plays a differential role in this task, creating tools to present multiple appealing information at the same time, using Color Blending Techniques. The results of this thesis determine valid paths to use color blending to transmit information.

5.1 Limitations

We consider that there were some limitations to this Master Thesis. First of all, the lack of users interested in participating in our user study was evident: we had to spend 20 Euros in a voucher card so the users would feel more interested. We think that, with an even larger user sample, the results of this color study would be majorly evident.

Another constraint was the location available to conduct the user laboratory study: the study had to be realized in rotating locations since there was no constant, quiet and well-located space for us to fulfill the user sessions. The absence of this factor would cause the broadcasting of the laboratory sessions to be much easier than what, in fact, was.

Regarding the implementation of the user study, we believe that the study could be implemented with some minor tweaks which have saved us some time: most of the data cleaning would be avoided if the collected data were saved in a different fashion (no *NONES*, the discarded information was not saved *a priori*). Moreover, the analysis could have been complemented with a statistical analysis in *R*[1], which is a free software environment for statistical computing and graphics, instead of solely *Matlab* and *SPSS*. Though *Matlab* provided useful tools to process the colors, it has revealed to have a longer-than-expected duration of implementation specially concerning a user study which comprised 32 different questions, whose individual analysis could not be standardized. On the other hand, *SPSS* has proved itself to have a steep learning curve, which delayed the statistical analysis.

Lastly, we believe that this research could have benefited if he had had another disclosure to users: if we had had the opportunity to broadcast this user study in other countries, we could have attained a sample of users culturally quite different, which could have enhanced the analysis of other cultural differences.

5.2 Future Work

This field of research has proved itself to have a tremendous potential, whereby there is a large set of questions which remain unanswered; this set is defined in the Discussion section of this thesis' Background (Section 2.3). Since the size of the user sample is a major concern when conducting user study like the one conducted by us, and calibration is an unavoidable issue, it would be interesting to conceive a remote calibration system which would be capable of rendering the web page container according to the user's LCD Display calibration.

Also, it would interesting to explore the color blendings of 3 colors, as Gama and Gonçalves did [GG14c], but with the goal of definitely determining if these color blendings have any chance of being used; it should be developed an entire study just to ascertain it. It could be also interesting to vary the parameters like Lightness, Luminance, Saturation, leading the user to explore different shades of a certain Hue: this could be also related to the aforementioned implication on color scales in Information Visualization.

[1]"The R Project for Statistical Computing", Available at: `r-project.org`. Last accessed on October 17th, 2016.

As referred in the Results Section (4.5), there is still room to improve and detail the comparison between color models which provide similar good values: these models are the HSV, RGB and CIE-L*a*b*. Respecting the color blendings, it could be further analyzed and deepen the relationship of human color perception with the Blue color: although it was the one which produced the weakest results of this color study, it still exerts some kind of influence on mental models of color of our users.

Comparing the results given with commonly-named colors was an important part of our analysis. Nonetheless, the comparison against the XKCD's Color Bins was not seamless: the generated bins and areas of coverage of each named color were not perfect, so it would be an interesting research topic to provide a comprehensive study about the naming of colors, in a laboratory environment.

It was mildly observable in our user study the theory that there is a difference in results between gender groups: further investigation could deepen if there is, in fact, any plausible difference between genders or age groups.

Finally, some color blending alternatives could be explored along with this technique, for example the Color Weaving, conveying user color studies to ascertain if there are concrete and valuable alternatives to the blending of colors.

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Appendix A

User Study Protocol

A.1 Motivation

By conducting this first study, we intend to:

- Conclude if there is any chance that cultural behaviours influence the user's color perception.
- Realize which color mixtures are more easily perceived by humans.
- Understand if, by using color, it is possible to clearly and easily convey information. This can be particularly interesting and useful when visualizing graphs or maps.
- Conclude if a person is capable of, not only building a mental color mixture model, but also deconstructing mixtures into their basic components.

A.2 User Profiling Phase

This study is anonymous and should take you up to 15 minutes. Please, answer the following answers accordingly.

A.3 Testing Calibration Phase

In this step, it's going to be presented to you a set of images. You should tune you screen definitions, in order to answer the questions, keeping them until the end of this study.

Please, follow the steps below indicated and answer the questions.

1. If possible, adjust your room lights for a comfortable usage of your device.
2. Avoid reflections on your screen, by diverting the screen from direct sources of light. This step is important, since light reflections can affect visualization of images.
3. To adjust the **Black Point** of your screen, define the Contrast and Brightness of your screen to their maximum.
4. After Step 3, gradually reduce **Brightness** value of your screen, in order to correctly distinguish the squares of each image below [calibration squares images].
5. If possible, define the **Color Temperature** of your screen to 6500 Kelvin Degrees.

6. You are now ready to answer the following questions!

NOTE: These 6 steps are only available to the Online Users, since the Laboratory Users do not need to perform these steps as the LCD display is already calibrated.

A.4 Testing Color Vision Deficiences Phase

This is the Color Vision Deficiencies Test.
In this step, it is going to be presented six plates with a colored pattern. Your job is to identify the number present in each plate, typing it down in the text box below. According to your answer, this test will inform us if you have any type of color vision deficiency which may undermine the job of color detection.

A.5 Core Test Phase

Choose the Resulting color which you believe it is the result of mixing the First and Second color, by adjusting the slider below the Resulting color.
Choose two colors with which you can achieve the Resulting color, by adjusting the sliders below each color.
NOTE: These instructions appear alternately, depending on the type of question which is shown.

Appendix B

Processing Data

In this Appendix, it is available a portion of the *Matlab* script which analyzed each question. Particularly, this section analyzes the Laboratory Regular users from Question 2, which concerns the blending of Red and Blue producing Magenta.

```
figure('NumberTitle','off');
cieplot();
title('Question 2: Laboratory Regular Users', 'FontSize', 13);              %% -- CHANGE HERE
xlabel('X Value');
ylabel('Y Value');
hold on;

scatter(x_pre_expectedColors(1), y_pre_expectedColors(1), 60, 'black', 'Filled');↙
% draw GIVEN COLOR
scatter(x_pre_expectedColors(2), y_pre_expectedColors(2), 60, 'black');↙
% draw EXPECTED COLOR
scatter(x_pre_expectedColors(3), y_pre_expectedColors(3), 60, 'black');↙
% draw EXPECTED COLOR

% Draw every pair of responses.
for i = 1 : height(laboratoryResults)
    %% Check if any Component is white or empty Answer
    sColor = str2num(cell2mat(laboratoryResults.second_color(i)));
    tColor = str2num(cell2mat(laboratoryResults.third_color(i)));

    if sColor == 0 || tColor == 0
        whiteAnswers = [whiteAnswers ; laboratoryResults(i,:)];
        rowsToEliminate = [rowsToEliminate i];
        continue
    end

    %% First Color - C1
    sColor = str2num(cell2mat(laboratoryResults.second_color(i)));      % cell2mat serve para↙
converter cell para matriz de uint
    valuesSColor = [valuesSColor sColor];                               % store integers↙
values of answers
    sColor = sColor/360;                                                % scale value to↙
[0,1] instead of [0, 360]
    sColor = [sColor 1 1];                                             % form triplet↙
(sColor, 1, 1)
    hsv_C1 = sColor;
    sColor = hsv2rgb(sColor);                                           % hsv -> rgb, values↙
between [0,1]
    rgb_C1 = round([sColor(1)*255 sColor(2)*255 sColor(3)*255]);
    sColor = rgb2xyz(sColor);                                           % rgb -> xyz
    x_aux = sColor(1)/(sColor(1) + sColor(2) + sColor(3));              % x = X / (X + Y + Z)
    y_aux = sColor(2)/(sColor(1) + sColor(2) + sColor(3));              % x = Y / (X + Y + Z)
    x_values = [x_values x_aux];                                        % store coordinates X↙
and Y
    y_values = [y_values y_aux];

    %% Second Color - C2
    tColor = str2num(cell2mat(laboratoryResults.third_color(i)));
    valuesTColor = [valuesTColor tColor];                               % store integers↙
values of answers
    tColor = tColor/360;                                                % scale value to↙
[0,1] instead of [0, 360]
    tColor = [tColor 1 1];                                             % form triplet↙
(tColor, 1, 1)
    hsv_C2 = tColor;
    tColor = hsv2rgb(tColor);                                           % hsv -> rgb, values↙
between [0,1]
    rgb_C2 = round([tColor(1)*255 tColor(2)*255 tColor(3)*255]);
    tColor = rgb2xyz(tColor);                                           % rgb -> xyz
    x_aux = tColor(1)/(tColor(1) + tColor(2) + tColor(3));              % x = X / (X + Y + Z)
    y_aux = tColor(2)/(tColor(1) + tColor(2) + tColor(3));              % x = Y / (X + Y + Z)
    x_values = [x_values x_aux];                                        % store coordinates X↙
and Y
```

```
    y_values = [y_values y_aux];

    %% Categorize Colors - Bins
    for j = 1 : length(colorBins)
        valuesofx = colorBins(j).XData;
        valuesofy = colorBins(j).YData;
        for a = 1 : length(valuesofx)
            if foundC1 == 0 && ((x_values(1) > (valuesofx(a) - 0.03) && x_values(1) <↙
(valuesofx(a) + 0.03)) && (y_values(1) > (valuesofy(a) - 0.03) && y_values(1) < (valuesofy(a)↙
+ 0.03)))
                color_C1 = colorBins(j).Tag;
                foundC1 = 1;
            end
            if foundC2 == 0 && ((x_values(2) > (valuesofx(a) - 0.03) && x_values(2) <↙
(valuesofx(a) + 0.03)) && (y_values(2) > (valuesofy(a) - 0.03) && y_values(2) < (valuesofy(a)↙
+ 0.03)))
                color_C2 = colorBins(j).Tag;
                foundC2 = 1;
            end
        end
    end

    if foundC1 == 0 && foundC2 == 0
        C1_name = [C1_name ; 'NA        '];
        C2_name = [C2_name ; 'NA        '];
    else if foundC1 == 1 && foundC2 == 0
            C1_name = [C1_name ; color_C1];
            C2_name = [C2_name ; 'NA        '];
        else if foundC1 == 0 && foundC2 == 1
                C1_name = [C1_name ; 'NA        '];
                C2_name = [C2_name ; color_C2];
            else
                C1_name = [C1_name ; color_C1];
                C2_name = [C2_name ; color_C2];
            end
        end
    end
    foundC1 = 0; foundC2 = 0;

    %% Difference between C1/C2 and expected colors C1/C2
    diff_c1_expected = round(pdist([[x_values(1) y_values(1)] ; [x_pre_expectedColors(2)↙
y_pre_expectedColors(2)]]), 2);  % [given -C1- C2]
    diff_c2_expected = round(pdist([[x_values(2) y_values(2)] ; [x_pre_expectedColors(3)↙
y_pre_expectedColors(3)]]), 2);  % [given C1 -C2-]
    distance_expectedC1C2 = [distance_expectedC1C2 ; diff_c1_expected + diff_c2_expected];

    %% Difference between C1/C2 blended onto Color Models against pre-calc values
    %%%%%% Blend-it in HSV
    sColor_hsv = [(hsv_C1(1)*360) hsv_C1(2) hsv_C1(3)]; tColor_hsv = [(hsv_C2(1)*360) hsv_C2↙
(2) hsv_C2(3)];
    diff_angles = abs(sColor_hsv(1) - tColor_hsv(1));
    if diff_angles > 180
        angle_small = (360 - diff_angles);  % smallest angle
        angle_small_half = angle_small / 2;
        sum_major = max([sColor_hsv(1) tColor_hsv(1)]) + angle_small_half;
        if sum_major > 360
            angle = rem((max([sColor_hsv(1) tColor_hsv(1)]) + angle_small_half), 360);
        else
            angle = max([sColor_hsv(1) tColor_hsv(1)]) + angle_small_half;
        end
    else
        angle = min([sColor_hsv(1) tColor_hsv(1)]) + (diff_angles / 2);
    end
```

```
    rColor = rgb2xyz(hsv2rgb(([angle/360 sColor_hsv(2) sColor_hsv(3)])));↙
% hsv -> rgb -> xyz -> compare
    x_aux  = rColor(1)/(rColor(1) + rColor(2) + rColor(3)); y_aux = rColor(2)/(rColor(1) +↙
rColor(2) + rColor(3));
    distance_HSV = [distance_HSV; round(pdist([[x_aux y_aux]; [x_pre_models(1) y_pre_models↙
(1)]]),2)];
    x_values_HSV = [x_values_HSV x_aux]; y_values_HSV = [y_values_HSV y_aux];

    %%%%%% Blend-it in CIE-LCh (XYZ -> Lab -> LCh)
    sColor_lch = sColor; tColor_lch = tColor;
    sColor_lch = applycform(sColor_lch, cformXYZ_Lab); tColor_lch = applycform(tColor_lch,↙
cformLab_LCh);

    l_aux = (abs(sColor_lch(1) - tColor_lch(1)) / 2) + min([sColor_lch(1) tColor_lch(1)]);  %↙
diff between colors, and add half to the smallest
    c_aux = (abs(sColor_lch(2) - tColor_lch(2)) / 2) + min([sColor_lch(2) tColor_lch(2)]);
    diff_angles = abs(sColor_lch(3) - tColor_lch(3));
    if diff_angles > 180
        angle_small = (360 - diff_angles);  % smallest angle
        angle_small_half = angle_small / 2;
        sum_major = max([sColor_lch(3) tColor_lch(3)]) + angle_small_half;
        if sum_major > 360
            h_aux = rem((max([sColor_lch(3) tColor_lch(3)]) + angle_small_half), 360);
        else
            h_aux = max([sColor_lch(3) tColor_lch(3)]) + angle_small_half;
        end
    else
        h_aux = min([sColor_lch(3) tColor_lch(3)]) + (diff_angles / 2);
    end
    rColor = applycform(applycform([l_aux c_aux h_aux], cformLCh_Lab), cformLab_XYZ);
    x_aux  = rColor(1)/(rColor(1) + rColor(2) + rColor(3)); y_aux = rColor(2)/(rColor(1) +↙
rColor(2) + rColor(3));
    distance_LCh = [distance_LCh; round(pdist([[x_aux y_aux]; [x_pre_models(2) y_pre_models↙
(2)]]), 2)];
    x_values_LCh = [x_values_LCh x_aux]; y_values_LCh = [y_values_LCh y_aux];

    %%%%%% Blend-it in CMYK
    sColor_cmyk = sColor; tColor_cmyk = tColor;
    sColor_cmyk = applycform(applycform(sColor_cmyk, cformXYZ_RGB), cformRGB_CMYK);↙
tColor_cmyk = applycform(applycform(tColor_cmyk, cformXYZ_RGB), cformRGB_CMYK);
    sColor_cmyk = [sColor_cmyk(1) sColor_cmyk(2) sColor_cmyk(3)]; tColor_cmyk = [tColor_cmyk↙
(1) tColor_cmyk(2) tColor_cmyk(3)]; %Exclude 'K' component
    c_aux = (abs(sColor_cmyk(1) - tColor_cmyk(1)) / 2) + min([sColor_cmyk(1) tColor_cmyk↙
(1)]);
    m_aux = (abs(sColor_cmyk(2) - tColor_cmyk(2)) / 2) + min([sColor_cmyk(2) tColor_cmyk↙
(2)]);
    y_aux = (abs(sColor_cmyk(3) - tColor_cmyk(3)) / 2) + min([sColor_cmyk(3) tColor_cmyk↙
(3)]);
    rColor = applycform(applycform([c_aux m_aux y_aux 0], cformCMYK_RGB), cformRGB_XYZ);
    x_aux  = rColor(1)/(rColor(1) + rColor(2) + rColor(3)); y_aux = rColor(2)/(rColor(1) +↙
rColor(2) + rColor(3));
    distance_CMYK = [distance_CMYK; round(pdist([[x_aux y_aux]; [x_pre_models(3) y_pre_models↙
(3)]]), 2)];
    x_values_CMYK = [x_values_CMYK x_aux]; y_values_CMYK = [y_values_CMYK y_aux];

    %%%%%% Blend-it in RGB
    sColor_rgb = sColor; tColor_rgb = tColor;
    sColor_rgb = applycform(sColor_rgb, cformXYZ_RGB); tColor_rgb = applycform(tColor_rgb,↙
cformXYZ_RGB);
    r_aux = (abs(sColor_rgb(1) - tColor_rgb(1)) / 2) + min([sColor_rgb(1) tColor_rgb(1)]);
    g_aux = (abs(sColor_rgb(2) - tColor_rgb(2)) / 2) + min([sColor_rgb(2) tColor_rgb(2)]);
    b_aux = (abs(sColor_rgb(3) - tColor_rgb(3)) / 2) + min([sColor_rgb(3) tColor_rgb(3)]);
    rColor = applycform([r_aux g_aux b_aux], cformRGB_XYZ);
```

```
    x_aux  = rColor(1)/(rColor(1) + rColor(2) + rColor(3)); y_aux = rColor(2)/(rColor(1) +↙
rColor(2) + rColor(3));
    distance_RGB = [distance_RGB; round(pdist([[x_aux y_aux]; [x_pre_models(4) y_pre_models↙
(4)]]), 2)];
    x_values_RGB = [x_values_RGB x_aux]; y_values_RGB = [y_values_RGB y_aux];

    %%%%%% Blend-it in CIE-Lab
    sColor_lab = sColor; tColor_lab = tColor;
    sColor_lab = applycform(sColor_lab, cformXYZ_Lab); tColor_lab = applycform(tColor_lab,↙
cformXYZ_Lab);
    l_aux = (abs(sColor_lab(1) - tColor_lab(1)) / 2) + min([sColor_lab(1) tColor_lab(1)]);
    a_aux = (abs(sColor_lab(2) - tColor_lab(2)) / 2) + min([sColor_lab(2) tColor_lab(2)]);
    b_aux = (abs(sColor_lab(3) - tColor_lab(3)) / 2) + min([sColor_lab(3) tColor_lab(3)]);
    rColor = applycform([l_aux a_aux b_aux], cformLab_XYZ);
    x_aux  = rColor(1)/(rColor(1) + rColor(2) + rColor(3)); y_aux = rColor(2)/(rColor(1) +↙
rColor(2) + rColor(3));
    distance_Lab = [distance_Lab; round(pdist([[x_aux y_aux]; [x_pre_models(5) y_pre_models↙
(5)]]), 2)];
    x_values_Lab = [x_values_Lab x_aux]; y_values_Lab = [y_values_Lab y_aux];

    scatter(x_values, y_values, 50, 'white');                           %draw two responses
    plot(x_values, y_values, 'Color', 'black');                        %draw relations between↙
answers
    x_values = [];                                                    %clean the arrays
    y_values = [];
end
hold off;

saveas(gcf, fullfile(path, 'lab_regularUsers'), 'png'); close;
laboratoryResults(rowsToEliminate, :) = []; rowsToEliminate = [];

% Centroids of Color Models
centroid_HSV    = [centroid_HSV  ; [round(mean(x_values_HSV),2) round(mean(y_values_HSV),↙
2)]];
centroid_LCh    = [centroid_LCh  ; [round(mean(x_values_LCh),2) round(mean(y_values_LCh),↙
2)]];
centroid_CMYK   = [centroid_CMYK ; [round(mean(x_values_CMYK),2) round(mean(y_values_CMYK),↙
2)]];
centroid_RGB    = [centroid_RGB  ; [round(mean(x_values_RGB),2) round(mean(y_values_RGB),↙
2)]];
centroid_Lab    = [centroid_Lab  ; [round(mean(x_values_Lab),2) round(mean(y_values_Lab),↙
2)]];

distance_centroid_HSV = [distance_centroid_HSV ; round(pdist([mean(x_values_HSV) mean↙
(y_values_HSV); [x_pre_models(1) y_pre_models(1)]]), 2)];
distance_centroid_LCh = [distance_centroid_LCh ; round(pdist([mean(x_values_LCh) mean↙
(y_values_LCh); [x_pre_models(2) y_pre_models(2)]]), 2)];
distance_centroid_CMYK = [distance_centroid_CMYK ; round(pdist([mean(x_values_CMYK) mean↙
(y_values_CMYK); [x_pre_models(3) y_pre_models(3)]]), 2)];
distance_centroid_RGB = [distance_centroid_RGB ; round(pdist([mean(x_values_RGB) mean↙
(y_values_RGB); [x_pre_models(4) y_pre_models(4)]]), 2)];
distance_centroid_Lab = [distance_centroid_Lab ; round(pdist([mean(x_values_Lab) mean↙
(y_values_Lab); [x_pre_models(5) y_pre_models(5)]]), 2)];

% Catenate all Tables              -- CHANGE HERE
diffs_table = table(distance_expectedC1C2, distance_HSV, distance_LCh, distance_CMYK,↙
distance_RGB, distance_Lab);

if size(C1_name, 1) == 1
    colors_names = cell(1,2);
    colors_names(1,1) = cellstr(C1_name);
    colors_names(1,2) = cellstr(C2_name);
    colors_names = cell2table(colors_names);
```

```
else
    colors_names = table(C1_name, C2_name);
end

C1_name = []; C2_name = [];

laboratoryResults = [laboratoryResults colors_names diffs_table];

% Plot Results for each Color Model
figure('NumberTitle','off');
cieplot();
title('Question 2: Laboratory Responses According to HSV Model', 'FontSize', 13);↙
%% -- CHANGE HERE
xlabel('X Value');
ylabel('Y Value');
hold on;
scatter(x_pre_models(1), y_pre_models(1), 50, 'black', 'Filled');          % Draw expected↙
response for this model
scatter(x_values_HSV, y_values_HSV, 50, 'white');                          % Draw responses↙
mixed in HSV
hold off;
saveas(gcf, fullfile(path, 'lab_HSVresponses'), 'png'); close;

figure('NumberTitle','off');
cieplot();
title('Question 2: Laboratory Responses According to CIE-LCh Model', 'FontSize', 13);↙
%% -- CHANGE HERE
xlabel('X Value');
ylabel('Y Value');
hold on;
scatter(x_pre_models(2), y_pre_models(2), 50, 'black', 'Filled');          % Draw expected↙
response for this model
scatter(x_values_LCh, y_values_LCh, 50, 'white');                          % Draw responses↙
mixed in LCh
hold off;
saveas(gcf, fullfile(path, 'lab_LChresponses'), 'png'); close;

figure('NumberTitle','off');
cieplot();
title('Question 2: Laboratory Responses According to CMYK Model', 'FontSize', 13);↙
%% -- CHANGE HERE
xlabel('X Value');
ylabel('Y Value');
hold on;
scatter(x_pre_models(3), y_pre_models(3), 50, 'black', 'Filled');          % Draw expected↙
response for this model
scatter(x_values_CMYK, y_values_CMYK, 50, 'white');                          % Draw responses↙
mixed in CMYK
hold off;
saveas(gcf, fullfile(path, 'lab_CMYKresponses'), 'png'); close;

figure('NumberTitle','off');
cieplot();
title('Question 2: Laboratory Responses According to RGB Model', 'FontSize', 13);↙
%% -- CHANGE HERE
xlabel('X Value');
ylabel('Y Value');
hold on;
scatter(x_pre_models(4), y_pre_models(4), 50, 'black', 'Filled');          % Draw expected↙
response for this model
scatter(x_values_RGB, y_values_RGB, 50, 'white');                          % Draw responses↙
mixed in RGB
hold off;
```

```
saveas(gcf, fullfile(path, 'lab_RGBresponses'), 'png'); close;

figure('NumberTitle','off');
cieplot();
title('Question 2: Laboratory Responses According to CIE-Lab Model', 'FontSize', 13);↙
%% -- CHANGE HERE
xlabel('X Value');
ylabel('Y Value');
hold on;
scatter(x_pre_models(5), y_pre_models(5), 50, 'black', 'Filled');          % Draw expected↙
response for this model
scatter(x_values_Lab, y_values_Lab, 50, 'white');                          % Draw responses↙
mixed in Lab
hold off;
saveas(gcf, fullfile(path, 'lab_Labresponses'), 'png'); close;

% Clean all the tables!
x_values_HSV = []; y_values_HSV = []; x_values_LCh = []; y_values_LCh = []; x_values_CMYK =↙
[]; y_values_CMYK = []; x_values_RGB = []; y_values_RGB = []; x_values_Lab = []; y_values_Lab↙
= [];
distance_HSV = []; distance_LCh = []; distance_CMYK = []; distance_RGB = []; distance_Lab =↙
[];
distance_expectedC1C2 = [];
```

Appendix C

Color Bins

In this appendix we include the map produced after XKCD's Color User Study, which shows the dominant names attributed to RGB colors over the faces of RGB cube.

C.1 Color Map

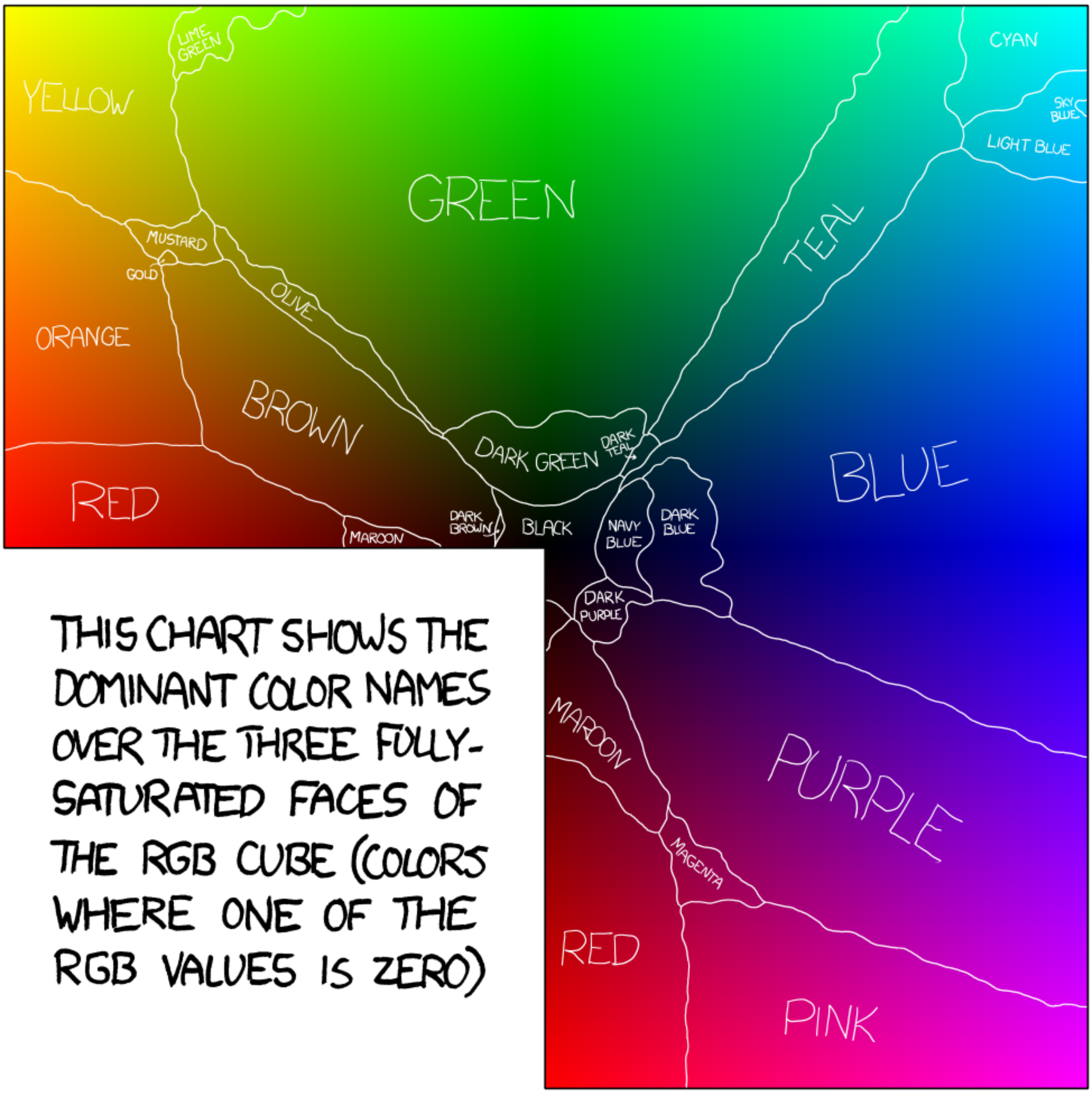

Figure C.1: XKCD Color Survey: map of color dominant names.