

Will It Blend?

Studying Color Mixing Perception

Paulo Duarte Esperança Garcia

Thesis to obtain the Master of Science Degree in
Information Systems and Computer Engineering

Supervisors: Prof. Dr. Daniel Jorge Viegas Gonçalves
Prof. Dra. Sandra Pereira Gama

Examination Committee

Chairperson: Prof. Dr. Someone
Supervisor: Prof. Dr. Daniel Jorge Viegas Gonçalves
Member of the Committee: Prof. Dr. Someone

October 2016

Acknowledgments

Agradecimentos.

Todos aqui.

Abstract

English Abstract goes here.

Keywords: one, two, three, keywords

Resumo

Resumo Português fica aqui.

Palavras-chave: uma, duas, três, keywords

Contents

List of Tables	xi
List of Figures	xv
Acronyms	xvii
1 Introduction	1
1.1 Dissertation Outline	1
2 Background	3
2.1 Theoretical Background	3
2.1.1 Color Perception	3
Color Philosophy	3
2.1.2 The Human Eye	4
Theories of Color Vision	6
Visual Deficiency	7
Mental Models and Codes	8
2.1.3 Color Models and Spaces	9
Colorimetry	9
Color Fundamental Concepts	9
Defining Color Models	11
Defining Color Spaces	13
Color Calibration	16
Color Usage	17
Color Organization	18
Color Scales	19
Color Blending	20
2.2 Related Work	20
2.2.1 Color Blending Research and Techniques	20
2.2.2 User Color Studies Online	21
2.3 Discussion	21
3 BlendMe!	23
3.1 Objectives	23
3.2 Designing the Solution	24
3.2.1 User Profiling Phase	24
3.2.2 Testing Calibration Phase	24
3.2.3 Testing Color Vision Deficiencies Phase	25

3.2.4 Core Test Phase	25
3.3 Evaluation Criteria	26
4 Analyzing Color Mixing Perception	27
4.1 Protocol	27
4.1.1 Laboratory Environment	27
4.1.2 Online Environment	28
4.1.3 Broadcasting the User Study	28
4.2 Data Cleaning	29
4.3 Data Processing	31
4.3.1 Data Preparation	31
4.3.2 Color Bins Comparation	33
4.3.3 Outputs Generated	35
4.4 Results	35
4.4.1 User Profile	36
4.4.2 Color Models	37
Analyzing Questions	38
Analyzing Color Models	51
Color Blending Expectation	61
4.4.3 Color Mixtures and Color Naming	64
Primary Colors	65
Color Blending Effort	69
4.4.4 Demographic Results	71
Age Groups	71
Gender Groups	73
Color Vision Deficient Users Group	74
4.5 Discussion	76
4.5.1 Calibration Resiliency	76
4.5.2 Creation of Color Scales	77
4.5.3 Color Organization	77
4.5.4 Implications for InfoVis	77
5 Conclusion	79
5.1 Limitations	79
5.2 Future Work	79
Bibliography	81
A User Study Protocol	83
A.1 Motivation	83
A.2 User Profiling Phase	83
A.3 Testing Calibration Phase	83
A.4 Testing Color Vision Deficiencies Phase	84
A.5 Core Test Phase	84
B Processing Data	85
C Chromaticity Diagrams	87

D Tables	89
D.1 Results Tables	89

List of Tables

3.1 Excerpt of Raw "Results" Table	26
4.1 Excerpt of Clean "Results" Table	31
4.2 XKCD Color Survey: Color Bins	34
4.3 Generated Outputs of Data Processing Phase	36
4.4 Results: Profiling Information (Gender and Academic)	36
4.5 Results: Profiling Information (Nationalities, Countries of Residence and Languages)	36
4.6 Results: Distances of Results Mixed in each Color Model	37
4.7 Question 1, with expected Results.	38
4.8 Question 2, with expected Results.	39
4.9 Question 3, with expected Results.	40
4.10 Question 4, with expected Results.	40
4.11 Question 5, with expected Results.	41
4.12 Question 6, with expected Results.	41
4.13 Question 7, with expected Results.	42
4.14 Question 8, with expected Results.	43
4.15 Question 9, with expected Results.	43
4.16 Question 10, with expected Results.	44
4.17 Question 11, with expected Results.	45
4.18 Question 12, with expected Results.	46
4.19 Question 13, with expected Results.	47
4.20 Question 14, with expected Results.	48
4.21 Question 15, with expected Results.	49
4.22 Question 16, with expected Results.	50
4.23 Question 17, with expected Results.	51
4.24 Laboratory Results: Statistics for distances <i>per</i> question, of Results Mixed in each Color Model	51
4.25 Condensed Statistics for Distances to Ideal Results, mixed in each Color Model.	52
4.26 Results: Distances of Results according to each Color Model, for questions 18 to 32.	61
4.27 Question 20, with expected Results.	61
4.28 Results of Blending Cyan and Magenta, obtaining Blue.	63
4.29 Condensed Statistics for Distances to Ideal Results, according to each Color Model, for questions 18 to 32.	64
4.30 Colors Models, ranked from best to worst, associated to every color blending studied.	64
4.31 Color Blends based on Primary Colors, which result in other Primary Colors.	65
4.32 Color Blending Effort, according to users' answers.	70

List of Figures

2.1	The Human Eye	4
2.2	Visible Spectrum of Light	4
2.3	Cones and Rods	5
2.4	Diagram of Eye Color Sensitivity	6
2.5	Correspondance of Colors Between Visual Deficiencies	7
2.6	Ishihara Plate	8
2.7	Himba Test: Green Color Ring	8
2.8	Trichromacy Theory	9
2.9	Hue, Saturation and Value Comparison	9
2.10	Luminance	10
2.11	RYB Color Model Schematic	11
2.12	RGB Color Model Schematic	12
2.13	HSV Triangle and Cone Representation	12
2.14	CMY(K) Color Model Representation	12
2.15	Half-toning	13
2.16	Munsell Color System Representation	14
2.17	CIE Horseshoe with AdobeRGB, sRGB and CMY(K) Gamuts	15
2.18	CIE-L*a*b*	16
2.19	Pantone Matching System - Marsala	16
2.20	Natural Color System Diagram	17
2.21	Adelson Illusion	18
2.22	Color Wheels Representing Primary, Secondary and Tertiary Colors	18
2.23	Color Schemes Wheels	19
2.24	Monochromatic Color Scheme	19
2.25	Spectrum Scale Example	19
2.26	Heated-Object Scale Example	20
3.1	Black Squares Test	25
4.1	XKCD Color Survey: Color Dominant Names	33
4.2	XKCD Color Survey: Color Bins Minimum Areas	34
4.3	Approximate Color Regions on CIE 1931 Chromaticity Diagram	34
4.4	XKCD Color Survey: Color Bins Transformation	35
4.5	Online Results: Answers for Question 10, from regular users.	44
4.6	Online Results: Answers for Question 10, from regular users, mixed in HSV Color Model.	44
4.7	Online Results: Answers for Question 11, from regular users.	45
4.8	Online Results: Answers for Question 11, from regular users, mixed in HSV Color Model.	45
4.9	Online Results: Answers for Question 3, from regular users, mixed in HSV Color Model.	46

4.10 Online Results: Answers for Question 12, from regular users, mixed in HSV Color Model.	46
4.11 Online Results: Answers for Question 10, from regular users, mixed in HSV Color Model.	47
4.12 Online Results: Answers for Question 13, from regular users, mixed in RGB Color Model.	47
4.13 Online Results: Answers for Question 9, from regular users, mixed in HSV Color Model.	49
4.14 Online Results: Answers for Question 15, from regular users, mixed in HSV Color Model.	49
4.15 Online Results: Answers for Question 16, from regular users.	50
4.16 Online Results: Answers for Question 16, from regular users, mixed in HSV Color Model.	50
4.17 Example of HSV Hue Circle, with opposed hue values.	52
4.18 Laboratory Results: Answers for Question 15, from regular users, mixed in HSV Color Model.	54
4.19 Laboratory Results: Answers for Question 16, from regular users, mixed in HSV Color Model.	54
4.20 Best and Worst Questions, according to HSV Color Model.	54
4.21 Online Results: Answers for Question 3, from regular users, mixed in CIE-L*C*h* Color Model.	55
4.22 Online Results: Answers for Question 6, from regular users, mixed in CIE-L*C*h* Color Model.	55
4.23 Best and Worst Questions, according to CIE-L*C*h* Color Model.	56
4.24 Online Results: Answers for Question 13, from regular users, mixed in CMYK Color Model.	57
4.25 Online Results: Answers for Question 17, from regular users, mixed in CMYK Color Model.	57
4.26 Best and Worst Questions, according to CMYK Color Model.	57
4.27 Online Results: Answers for Question 6, from regular users, mixed in RGB Color Model.	58
4.28 Online Results: Answers for Question 13, from regular users, mixed in RGB Color Model.	58
4.29 Best and Worst Questions, according RGB Color Model.	59
4.30 Laboratory Results: Answers for Question 6, from regular users, mixed in CIE-L*a*b* Color Model.	60
4.31 Online Results: Answers for Question 6, from regular users, mixed in CIE-L*a*b* Color Model.	60
4.32 Best and Worst Questions, according to CIE-L*a*b* Color Model.	60
4.33 Online Results: Answers for Question 20, from regular users.	62
4.34 Online Results: Answers for Question 17, from regular users, mixed in CIE-L*a*b* Color Model.	63
4.35 Online Results: Answers for Question 32, from regular users.	63
4.36 Online Results: Answers for Question 8, from regular users.	66
4.37 Online Results: Answers for Question 25, from regular users.	66
4.38 Online Results: Answers for Question 17, from regular users.	67
4.39 Online Results: Answers for Question 32, from regular users.	67
4.40 Laboratory Results: Answers for Question 7, from regular users.	67
4.41 Online Results: Answers for Question 7, from regular users.	67
4.42 Online Results: Answers for Question 2, from regular users.	68
4.43 Online Results: Answers for Question 19, from regular users.	68
4.44 Online Results: Answers for Question 1, from regular users.	69
4.45 Online Results: Answers for Question 18, from regular users.	69
4.46 Answer-pairs with one white component, from Question 10.	71
4.47 Answer-pairs with one white component, from Question 15.	71
4.48 Demographic Results, from Question 6, for answers given by users aged below 20 years, blended according to HSV Color Model.	73

4.49 Demographic Results, from Question 6, for answers given by users aged between 40 and 49 years, blended according to HSV Color Model.	73
4.50 Demographic Results, from Question 16, for answers given by female users, blended according to RGB Color Model.	75
4.51 Demographic Results, from Question 16, for answers given by male users, blended according to RGB Color Model.	75
4.52 Online Results: Answers for Question 8, from regular users.	75
4.53 Online Results: Answers for Question 8, from daltonic users.	75
4.54 Laboratory Results: Answers for Question 17, from daltonic users.	76
4.55 Online Results: Answers for Question 17, from daltonic users.	76

Acronyms

CMYK Cyan, Magenta, Yellow, Key. 31, 32

CSV Comma Separate Values. 29, 30, 35

HSV Hue, Saturation, Value. 31, 32

InfoVis Information Visualization. 35

IST Instituto Superior Técnico. 28

RGB Red, Green, Blue. 31–33

RNL Rede Novas Licenciaturas. 28

RYB Red, Yellow, Blue. 57

Chapter 1

Introduction

Introduction goes here.

... USAR ESTA PARTE DA INTRODUÇÃO DO RESEARCH PROPOSAL ...

In this section, we introduce the majority of topics to be further studied, the different phases of our research, the metrics we are going to collect and how we are going to treat them. Since we aim to *study to what extent can a user distinguish different amounts of blended colors, when using color mixtures to convey information*, it is important learn from previous results, testing out not only the validity of them but also some missed opportunities.

There are several aspects to be considered when developing the broadest study possible: regarding color blending profiling tests, it exists - among others - some questions which remain unanswered; some of them were risen in the studies by Gama and Gonçalves [GG14b, GG14a]. These questions can be divided in four categories:

1.1 Dissertation Outline

Describe the organization of the dissertation document, referring to other chapters.

Chapter 2

Background

2.1 Theoretical Background

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 questions¹, 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 **eliminativism** 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. Chiramuuta 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 questions, we can derive even more theories: **Primitivism**, **Reductive Physicalism**, **Dispositionalism**, **Projectivism**, **Subjectivism**, among others.

Chiramuuta [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 affirms, his view is close to **Relationism**, a

¹“Stanford Encyclopedia (...)", Available at: stanford.io/1Mwp7Zh. Last accessed on January 8th, 2016.

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.

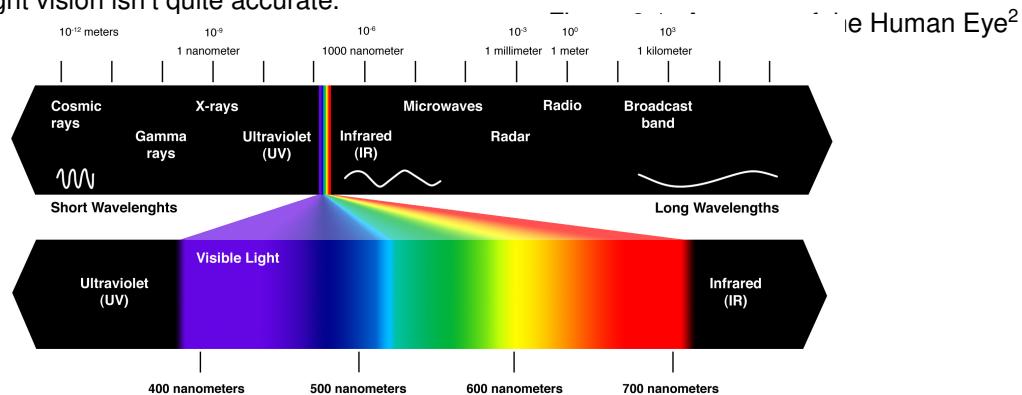
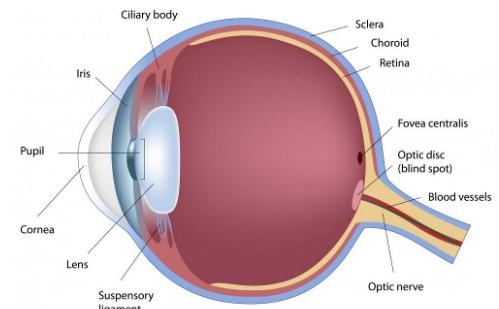


Figure 2.2: Visible Spectrum of Light.³

Light is electromagnetic radiation, but most of this radiation is invisible to the human eye: it can perceive light from under 400 nanometers until 750 nanometers, as seen on figure 2.2.

When the light strikes an object, depending of the surface's material, it can either: be wholly or partly absorbed, reflected or transmitted; what we perceive as being an object is the light reflected of the surface. The human eye (Figure 2.1), 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.

²"Anatomy of The Eye", Available at: bit.ly/1UAxGyA. Last accessed on January 8th, 2016.

³"Claude Monet (...)", Available at: bit.ly/10Ssw2Q. Last accessed on January 8th, 2016.

⁴"The Human Eye and Adaptive Optics", Available at: bit.ly/1zMEgK6. Last accessed on January 8th, 2016.

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**, where the light rays entering the lens are focused.

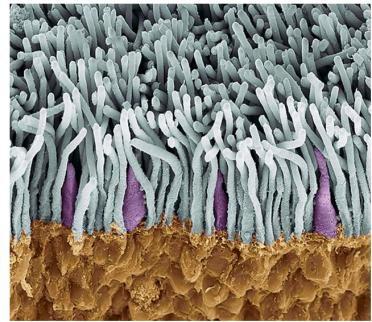


Figure 2.3: Representation of Cones and Rods.⁴

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**.

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 2.3 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 2.3); 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 2.4, it is possible to compare the light absorbance for different wavelengths, distributed among Cones and Rods.

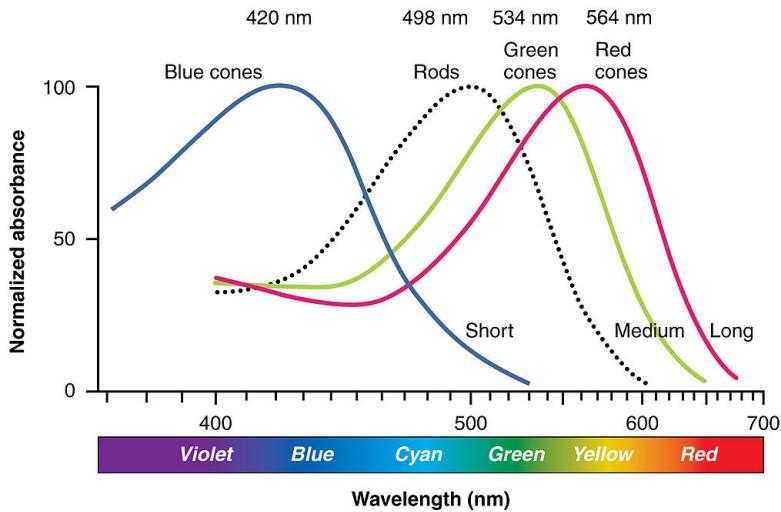


Figure 2.4: Diagram of Eye Color Sensitivity, depicting distribution between cones and rods.⁵

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 suggests that our color perception is controlled by three opponent pairs: red and green, blue and yellow, white and black⁶. Hering postulated that the members of each pair either oppose or inhibit each other, only one element can be signaled at one time, but not both at the same time: when one member of an opponent pair is no longer stimulated, the opponent pair is activated. For example, if you stare for a long period of time to a red subject, when you look away the afterimage will be red.

Together, these theories summarize what we know about color vision. We perceive color because of the three photoreceptors in our retina and sense different colors when there exist different ratios in the three cone cells. The Trichromatic Theory explains how we see what we see in color, but it is only valid for the presence of all types of cells. However, it has to be considered the case in which these cells are totally or partially absent.

⁵"Photoreceptor Cell", Available at: bit.ly/1VNZQHE. Last accessed on January 8th, 2016.

⁶"How to See Impossible Colors (...)", Available at: bit.ly/1ZdtSKv. Last accessed on January 8th, 2016.

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 or Alzheimer's disease. These deficiencies can be classified as follows:

- **Monochromacy:** Known as “total color blindness” and is caused by cone defect or total absence of it. It occurs when two or all three types of cones don’t exist and color and lightness detection is reduced from three dimensions, to only one. This condition is reasonably rare.
- **Dichromacy:** In this defect, one of the possible three cone chemical protein is missing. Is is an hereditary condition and it occurs when when one of the cone pigments doesn’t exist. Dichromacy can be divided into three conditions:
 - Protanopia (from the Greek *prot-*), refers to the absence of red retinal photoreceptors. Protans find hard to distinguish between red and green colors and blue and green colors.
 - Deutanopia (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.
- **Trichromacy:** In this defect, one of the three cone pigments is altered in its spectral sensitivity. Also, it can be divided into three conditions: Protanomaly, Deutanomaly (which is the most common color vision deficiency in the world, affecting 5% of European Males) and Tritanomaly.

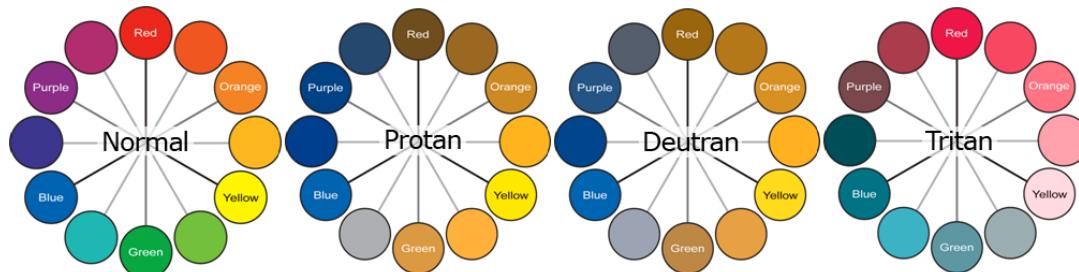


Figure 2.5: Correspondence of Colors Between Normal Vision, Protanopia, Deutanopia and Tritanopia.⁷

Figure 2.5 presents the color differences between a person with a normal visual condition, a protan, a deutan and a tritan.

Color deficiency can be diagnosed through an eye examination. During that test, it will be used specially designed figures composed with colored dots, called **Pseudisochromatic Plates**, which include a number or a figure supposed to be easily decoded by someone without a visual deficiency, as the example of the figure 2.6. 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;

⁷“What About Color Blindness?”, Available at: bit.ly/107IK4G. Last accessed on January 8th, 2016.

⁸“Ishihara Color Test”, Available at: bit.ly/1jp31m3. Last accessed on January 8th, 2016.

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, as an important first verification.

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 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 now⁹ [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 documentary¹⁰ 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 2.7), 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.

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.

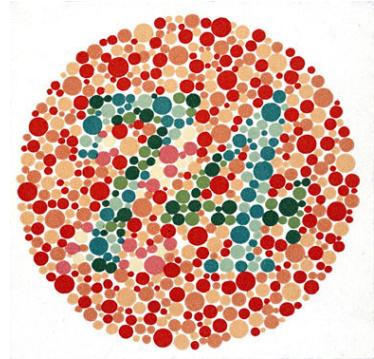


Figure 2.6: Pseudosochromatich Plate, with number 74.⁸

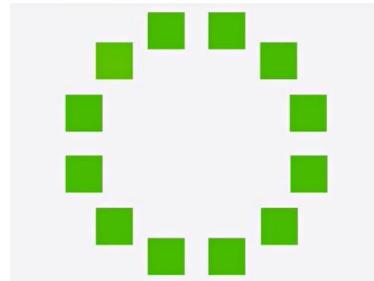


Figure 2.7: Example of a Green Color Test made.¹⁰ to the Himba tribe from Northern Namibia. Surprisingly, they were able to detect a larger number of shades of green than a western, non-colorblind person: this may occur because their environment do not manifest as much colors, and they need to detect different shades to hunt and pick up vegetation and fruits, which traditional western communities do not need to do.

⁹"Where Man See White (...)", Available at: bit.ly/1AMHgcW. Last accessed on January 8th, 2016.

¹⁰"It's Not Easy Seeing Green". Available at: nyti.ms/1S71yVo, Last accessed on January 8th, 2016.

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 [War]:

$$C = sS + mM + lL \quad (2.1)$$

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 to maintain and calibrate standardized lamps, special instruments to evaluate color precision would be very expensive and this would not be very practical.

To solve this, it was assumed that every human being had about the same sensitivities to different colors (excluding the obvious color deficiencies), and the same receptor functions; it was the time to start creating color specification standards and understand the principal concepts of it.

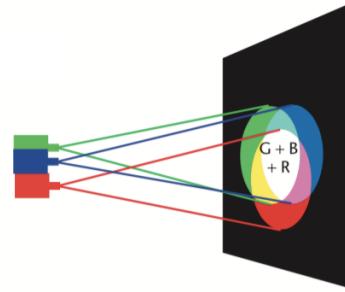


Figure 2.8: A Color-matching setup [War]

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. These concepts are listed below, with an appropriate explanation seeking them.



Figure 2.9: Comparison between Hue, the concept of Saturation and Lightness (or Value).¹¹

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

¹¹“How to Analyze Data (...)", Available at: bit.ly/1KHHtg2. Last accessed on January 8th, 2016.

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 2.9, 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 perceptual 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 2.9, 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 2.9): 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.

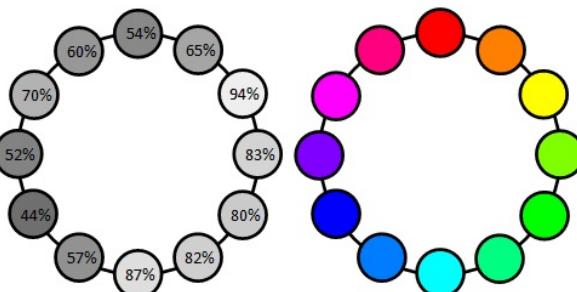


Figure 2.10: Luminance schematic.¹²

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 2.10 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.

¹²"Color Luminance", Available at: bit.ly/2203vdp. Last accessed on January 8th, 2016.

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 tends 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 [War].

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.

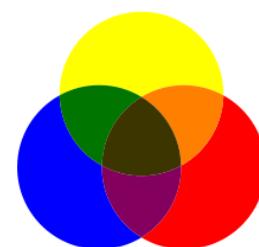


Figure 2.11: RYB Color Model.¹³

¹³“RYB Plano”, Available at: bit.ly/22MHzPJ. Last accessed on January 8th, 2016.

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. 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.

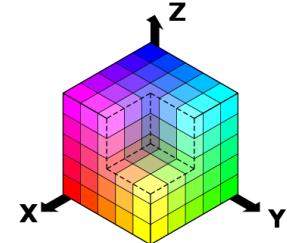


Figure 2.12: RGB Color Model.¹⁴

This color model is represented as three dimensional cube, with each corner being the purest colors, as in the Figure 2.12.

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 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,

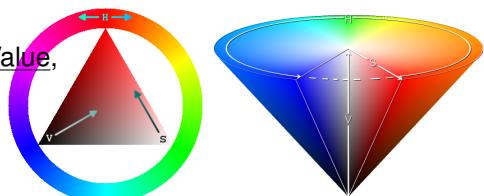


Figure 2.13: HSV Color Model.¹⁵

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**.

CMY(K) CMY(K) works as a subtractive color model, with four color components, and is primarily used in printing industries, given the feature of printed ink of reducing the light that otherwise would be reflected. It is composed by four color: Cyan-Magenta-Yellow-Key. Key value is representing

¹⁴"RGB Cube", Available at: bit.ly/1n5QcdZ. Last accessed on January 8th, 2016.

¹⁵"Computer Graphics (CS 4300) (...)", Available at: bit.ly/10Qh8Vh. Last accessed on January 8th, 2016.

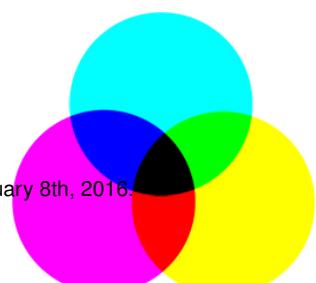


Figure 2.14: CMY(K) Color Model.¹⁶

the black color, which is used because the combination of the three primaries does not produce a fully saturated black color. This color model is able to produce the entire color spectrum of visible colors, due to the **half-toning** process it executes: tiny dots of each primary color, with an assigned saturation, are printed in a pattern small enough so it is perceived as a solid color. This process allows the printing of more than seven colors, the amount of possible mixture combinations which could be created if the primary colors were printed as a solid block of color. In order to improve the print quality and reduce moiré patterns, the screen for each color is set at a different angle. This configuration is shown in Figure 2.15.

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

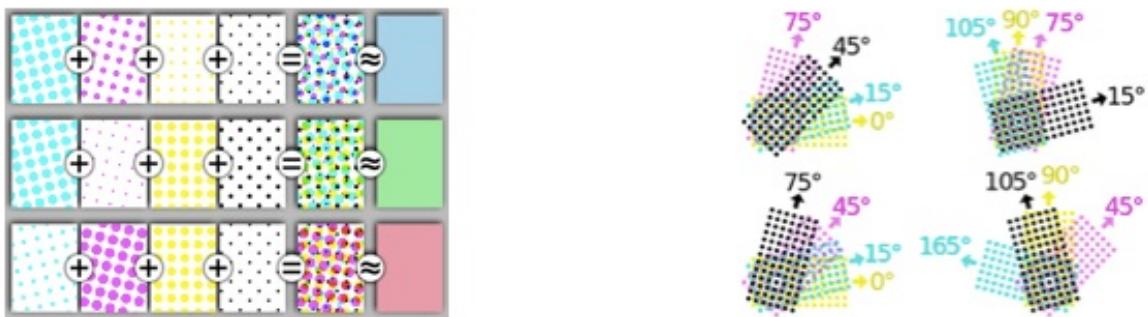


Figure 2.15: Half-toning patterns presented on the left image and different angles at the right image.¹⁷

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.
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.

¹⁶"What is the difference (...)", Available at: bit.ly/10hu0lp. Last accessed on January 8th, 2016.

¹⁷"Halftone", Available at: en.wikipedia.org/wiki/Halftone. Last accessed on January 8th, 2016.

¹⁸"Munsell Color System", Available at: bit.ly/1mJsh3I. Last accessed on January 8th, 2016.

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.

Each circle of the cylinder is divided into five principal hues: Red, Yellow, Green, Blue and Purple, where intermediate hues can be found in-between the principal ones. Two colors with equal chroma and value - residing in the same circle - but found on opposite sides are complementary colors, and create gray color found in center of the circle, when mixed together. Colors in this system are defined in the format “**H V/C**”, for example, “5R 5/10” means Red Hue, with 5 meaning middle value and a chroma of 10, indicating a high level of purity. In Figure 2.16, it is represented the circle of hues at value 5 and chroma 6, most precisely chromas for Purple-Blue. This color system is still in usage nowadays, being the basis for numerous models such as **CIE-L*a*b***.

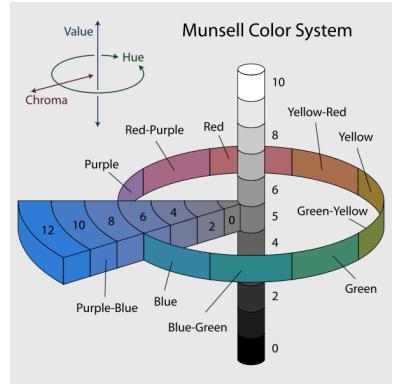


Figure 2.16: Munsell Color System.¹⁸

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.

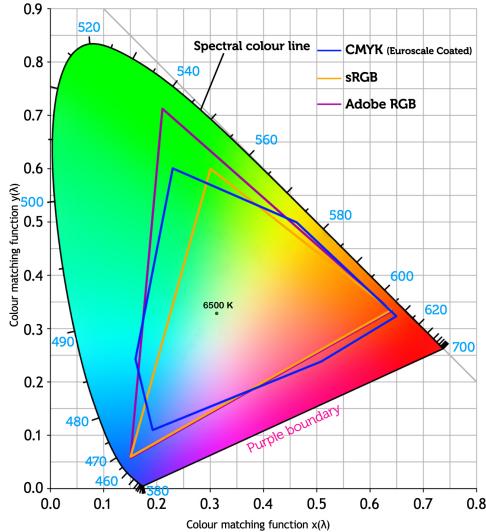


Figure 2.17: CIE Color Diagram, with CMY(K), sRGB and AdobeRGB Color Gamuts depicted.¹⁹

The CIE 1931 color diagram, as seen on the Figure 2.17, represents all the chromaticities visible to an average person, called the gamut of human vision., in particular several subsequent RGB color spaces, such as the **sRGB** (the most commonly used RGB space, in media devices), the **Adobe RGB and Apple RGB** which define their own particular gamut of colors. 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 [War]:

- 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:

$$x = 0.313, y = 0.329 \quad (2.2)$$

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

$$x = 0.448, y = 0.407 \quad (2.3)$$

which is considerably more yellow than normal daylight.

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

The CIE Color System is both a Color Model and a Color Space since, at the same time, it describes a mathematical representation using XYZ primaries and represents the superset of the entire range of human perceivable colors. The **CIE RGB Color Space** is one of the many subsets of CIE XYZ.

¹⁹"CMYK Colour Model/Colour Space", Available at: bit.ly/1TIo5pd. Last accessed on January 8th, 2016.

²⁰"CIELAB, Adobe Technical Guides", Available at: bit.ly/1RmIZwL. Last accessed on January 8th, 2016.

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

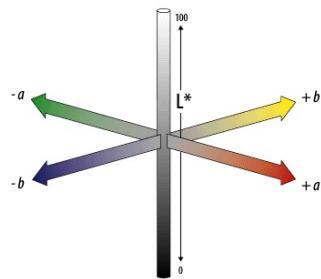


Figure 2.18: CIE-L*a*b* axis.²⁰

There are some particularities related to this space, which can be seen on Figure 2.18: **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.

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

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 2.19: Pantone 18-1438 Marsala.²¹

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 2.19). 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 paper²¹. 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 [War]. 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 to²²:

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 your shade or tint in the color triangle of the color chosen in the first step. This will give you its darkness and chromaticity, which must add up to 100%: if a percentage value remains, it is attributed to whiteness.
3. Write the full name, preceding with "NCS", adding "S" if the color is an NCS standard color.

For example, **NCS S 1070-Y10R** translates into a NCS standard color perceived as: 90% Yellow and 10% Red, with 10% of Whiteness and 70% of Chromaticity value. Since $10\% + 70\% = 80\%$, the remaining 20% belongs to *Whiteness*. This color is shown in Figure 2.20.

Color Usage

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

²¹"The Pantone Matching System®", Available at: bit.ly/1ZdsYNU. Last accessed on January 8th, 2016.

²²"How To Communicate Your Color.", Available at: bit.ly/10Srttz. Last accessed on January 8th, 2016.

²³"Adelson's Same Color Illusion", Available at: bit.ly/10QgpDg. Last accessed on January 8th, 2016.

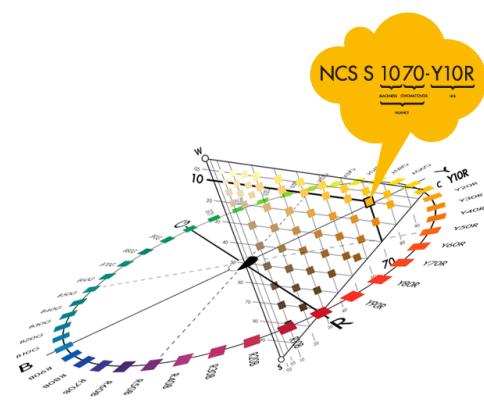


Figure 2.20: NCS S 1070-Y10R.²²

darkness, the chromaticity and a percentage value between two of the colors

The color of an object, as we have discussed before on Section 2.1.1, is both environmental and perception-dependent. Physically, the perceived color is related to the color of light that leaves the surface of the object, which depends of the color spectrum of the light source and reflectance properties of the material, besides the angle formed between the light source and the surface of reflectance, or even the angle of view. Materials have different behaviors, they can transmit, reflect or emit light, being the latter a contributor to the perceived color also: if the electrons are excited due to high temperatures is created a **incandescence** phenomenon, or **phosphorescence** if the light is absorbed at a shorter wavelength than the light that is emitted. Apart from these behaviors, perception is modified by the surroundings of the color: the Adelson Illusion (Figure 2.21) is a perfect example to prove that the human perception system is gifted with the feature of Color Constancy, that let us perceive that a color is still the same color, regardless of the background, lighter or darker. For example, an apple is an apple in the morning when the sun rises, it is the same apple in the sunset and it is the same apple at night, we perceive the object as equal independently of the lighting conditions; this helps us to recognize objects. In the illusion of Figure 2.21, the orange circle in the shadow appears brighter than the other circle but they are, in fact, exactly the same shade of orange.

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

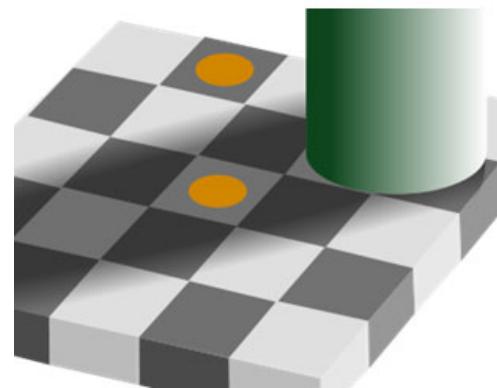


Figure 2.21: The Adelson Illusion.²³

Color Organization

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

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



Figure 2.22: Color Wheels representing Primary, Secondary and Tertiary Colors.²⁴

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

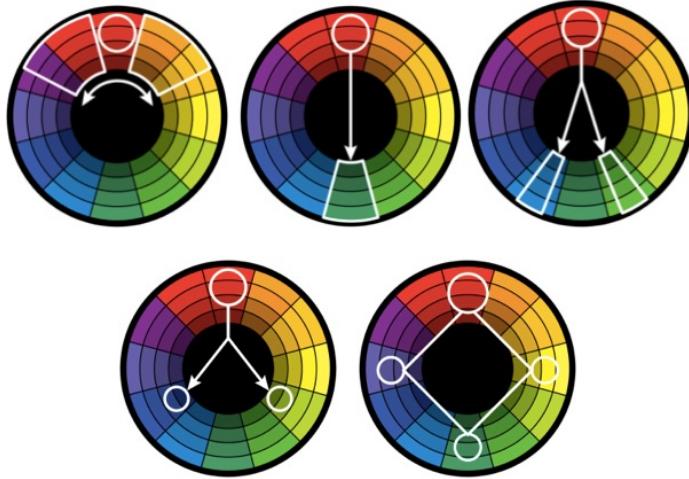


Figure 2.23: Color Wheels Representing on the first row Analogous, Complementary and Split Complementary. On the second row, Triadic and Tetradic Color Schemes.²⁵

This allows us to use harmony to create an equilibrium, which some theories already cover: these theories are called **Color Schemes**, that can be used over a numerous types of information channels, including the web. There are a few schemes already in use, which are listed below: Analogous, Complementary, Split Complementary, Triadic, Tetradic, all shown in Figure 2.23, and Monochromatic, in Figure 2.24.



Figure 2.24: Monochromatic Color Scheme.²⁶

Color Scales

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

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 2.25) is a very commonly used scale, keeping the saturation and brightness invariables, oscillate hue within its full

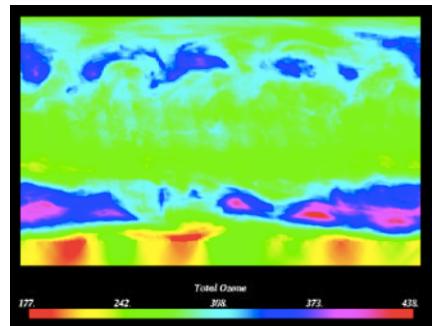


Figure 2.25: Spectrum Scale. [Rhe00]

²⁴"Understanding Color Theory", Available at: bit.ly/1TInJ1V. Last accessed on January 8th, 2016.

²⁵"Color Harmony (...)", Available at: bit.ly/18gWJER. Last accessed on January 8th, 2016.

²⁶"Understanding the Qualities (...)", Available at: bit.ly/07ieye. Last accessed on January 8th, 2016.

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 observers²⁷: 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 2.26) 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.

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.

Color Blending

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

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

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

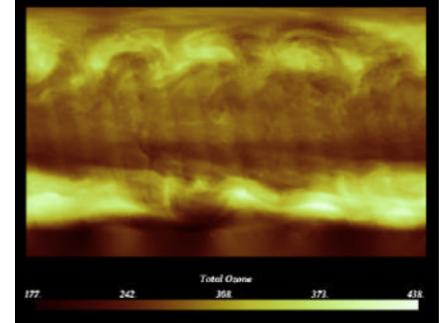


Figure 2.26: Heated-Object Scale. [Rhe00]

2.2 Related Work

2.2.1 Color Blending Research and Techniques

Ver se houve desenvolvimentos na área em 2016.

²⁷“Dear NASA (...”, Available at: blog.visual.ly/rainbow-color-scales/. Last accessed on January 8th, 2016.

2.2.2 User Color Studies Online

Ler artigos do David Flatla, investigar se existe trabalho feito na área nos últimos meses.
Procurar artigos do CHI.

2.3 Discussion

Discutir aqui possíveis questões que podem ser abordadas.

- **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 *really* 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 there are these questions whose answers remains to be found, 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 intended to perform **three studies** and, in the following sections, it is covered the entire proposal for the first study, the conditions in which the study is ideally performed and other important details.

Chapter 3

BlendMe!

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 are as follows:

1. Study one way to present color which does not influence color perception.
2. Understand if there is any psychological organization of color, when detailing color mixtures' components.
3. If possible, obtain results to ascertain the cultural influence in color perception.
4. Study the influence of discrete and continuous color scales.

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).

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

- **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?
- **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 additive**, 4. **Analyze the ease of blending colors**, or if 5. **There is substantially different results among genders, or different age groups**.

Justificar nome

Referir HSL com hue variante, e SL com parametros maximos.

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 sections, we detail each of these sections.

3.2 Designing the Solution

Design the implementation, talk about the process ever since wireframing, through the mapping of concepts between what we want and how we implemented, in order to achieve what we want. Include screenshots from the implementation.

Important detail: color conversion between Excel and adapted colors with ICC profile, Spyder and all. ColorConverter.m.

Dividir secção em partes do estudo, introduzindo com Research Proposal para motivar decisões. Referir todos os detalhes de implementação. Justificar completamente todas as decisões que foram tomadas (número de placas, informações pedidas, métricas colhidas, tudo.) Falar de folha de calculo do excel com todas as cores, que depois for migrada para matlab e convertida de acordo com perfil de calibração.

One of the points discussed in section 2.3 was the amount of users who performed the study of Gama and Gonçalves [GG14b, GG14a]: 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, trying to take advantage of the cultural diversity that may arise. These online answers will become from online users from social networks, in which we will spread our study in a *word-of-mouth* scheme.

3.2.1 User Profiling Phase

FALTA TEXTO AQUI...

In this phase of the study, questions about the Age, Gender, Academic Degree, Nationality, Country of Residence and the Native Language of the user should be asked: these questions will help us conceiving user profiles with key indicators about cultural background and gender relation to results of each test.

(... ACRESCENTAR AQUI MAIS INFOS RELEVANTES ...)

When this phase is concluded, the user will be guided to another stage of the study, to perform the **Calibration Phase**, where he will be 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 on how it is guaranteed 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 is 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. Since we have not found a way to tackle this solution so far, we developed another solution: to present, as pre-step, some calibration images in which the user will have to perform a set of small tasks, indicating us a set of answers; in the end of the test, 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.

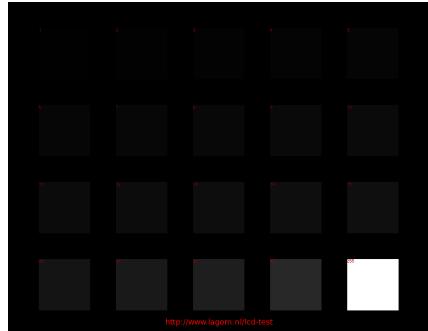


Figure 3.1: Example of Black Squares Test.¹

We will present to the user a **pair of images**, consisting of a set of 10 squares each; in the first of them, we will test the black level of user's monitor, showing each square with a different shade of black, from brighter ones (Square 1) to darker ones (Square 10). The user is, then, asked to express which square is the last, most perceivable, darker square, and point out the word which follows it. The second image has the same job as the first one, except that this rules out the white-level of the monitor and the ten squares present different tones of white. An example of this sort of test is presented in Figure 3.1. The results of this phase are recorded for further analysis when the study finishes.

Regarding the laboratory environment, we are going to conduct the user tests in a LCD monitor, under a fixed light source; the monitor will be calibrated using a colorimeter which will consider the existing light in the environment and adjust the color of each pixel to a standard. The user will be focused on the task and no other user will be present in the room at the same time, excluding the study regulator; the user will have a fully detailed test protocol to follow. (... FALTA TEXTO AQUI ...) Referir limitação descoberta entre Chrome Safari

3.2.3 Testing Color Vision Deficiencies Phase

3.2.4 Core Test Phase

Incluir tabela com todas as cores, igual a folha de auxilio. Referir que Ciano, por erro, não esta a ser testado no formato objTwoColors.

Referir aqui que dados estão a ser guardados do utilizador, e como estão a ser guardados, (objTwoColors e twoColorsObj), etc. Referir aqui também que slider contemplava cores standard da folha de calculo para ambiente online, mas para ambiente laboratorio cores eram antes processadas no Matlab. Slider não tinha cores ordenadas para que utilizador não utilizasse algum modelo mental e aprendesse previamente a misturar. Cores foram misturadas sem qualquer critério (referir ordem pela qual apareciam). Referir aqui caminho do calibrador -> icc -> matlab -> converter cores -> slider

¹"Black Level", Available at: www.lagom.nl/lcd-test/black.php. Last accessed on September 7th, 2016.

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
5745c1c07cc0	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	#FFF00	#46F9C	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 3.1: Excerpt of Results Table, with raw data.

3.3 Evaluation Criteria

Ishihara plates and more, whatever we consider relevant. Falar também de como a calibração era considerada válida ou não. Erros que poderiam ser gerados pelo field number html5, que com scrolls podia dar valores errados.

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 was 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 describing 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 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 display was everytime fully calibrated, since the software manifested an erratic behaviour when using the other functions: the screen colors were presented in a very warmer/colder color profile than it was before.

The tests were conducted at, most of the repetitions, in Rede Novas Licenciaturas (RNL) at Instituto Superior Técnico (IST), and fewers 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 undeneath a fixed incadescent 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 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, it was asked the user 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 maniupulate the color calibration of online user's LCD display, using a software piece which would acquire important informations 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 controled 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 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(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 in a Relational Database.

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 either 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, bringing 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 the users were not willing to fulfill the study. We had even 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 representative cultural diversity to analyze. In the final phase of our study, we raffled a FNAC 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* sub-thread 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 four-hundred and seventy-nine (477) users** which interacted with our study and fulfilled, at least, until the Color Vision Deficiencies Test Phase. However, only **two-hundred and sixty-one (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, leaving the other two hundred and eighteen (218) users which did not leave any answer, defining the remaining percentage **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 present 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 along 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, Comma Separate Values (CSV) files were exported from each table using a PostgreSQL for macOS called *Postico*¹, which originated 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 Laboratory

¹ Postico - a modern PostgreSQL client for the Mac. Available at: eggerapps.at/postico/. Last accessed on September 11th, 2016.

Results, Online Results and demographic results: concerning the age, we divided it on Users aged below 20 Years Results, Users aged between 20 and 29 Years Results, Users aged between 30 and 39 Years Results, Users aged between 40 and 49 Years Results, Users aged between 50 and 59 Years Results and Users aged above 60 Years Results. Respecting the division of genders, we created the categories Female Users Results, Male Users Results and Other Gender Users Results. We have **not** excluded nor the users which provided answer to only one question from the 32 question set, or 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 stored in columns *First Color*, *Second Color* and *Third Color*, since this is redundant because it 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** - This step was performed just after the previous one. 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, giving us much more precision than what is, in fact, needed considering that the hue is measured in terms of integer numbers. The number was rounded up to its closest integer number, then. Besides that, there was still one value to be adjusted which was the missing response: *NONE* needed to be replaced by 0, to simplify the processing of null answers.
- **Sort Entries** - In order to favour 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** - As previously said, to perform the Laboratory Study we used a Spyder Color Calibrator to manage the color representation independently of the environmental conditions of light. Since the Color Profile file generated by the calibrator was used to adapt colors to be presented to the user, those same colors had to be trackbacked to the original color, for the sake of normalization of values. This is specially 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** - Regarding the "Profiling" data, there was some which was 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) and other languages, 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 tables contained many entries from users that performed the study with incorrect calibration and from users which gave unexpected values on the color deficiencies test phase; the entries which corresponded to a user that failed all 6 values on the later phase, would be deleted, leaving no trace of its participation. 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 4.5.1. To end up the cleaning phase, it was decided to treat the color deficient users independently: we 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. More tables can be found in Appendix D, specifically Section D.1.

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.

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 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, blend the values to check which color model answers are closer to (either Hue, Saturation, Value (HSV), Red, Green, Blue (RGB), Cyan, Magenta, Yellow, Key (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 of 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 it is, 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 no 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, it was mandatory to convert the color to a common color standard: for that reason, 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 of the 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 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.

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

An example of linear interpolation between primitives can be seen on Equation 4.1, in which we blend RGB primitives. The listing 4.1 shows how the angular interpolation is being calculated with our *Matlab* script.

Listing 4.1: Excerpt of *Matlab* code which interpolates the angular Hue 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
```

Afterwards, every resulting blending is **compared to the pre-calculated value for each color model**; the distance to the late 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 expected 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 this comparisons, the centroids of each set of colors mixed in every color model are calculated, along with its distance to the expected pre-calculated answer.

This computation is applied to all questions from 1 to 17, when the resultant color is given and two answers expected. However, there are some differences when processing data from questions 18 to 32,

which are questions where the two primitive colors are given and the resulting color is expected, 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; it is only calculated the distance of the answered color, to the expected one.

4.3.2 Color Bins Comparation

This analysis phase had a very important step, which was to assign meaning to the answers given by the users: **to attribute names to colors indicated**, whose to be commonly used by the users. 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*² had already conducted a widely large Color Survey³ to study which 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 (Figure 4.1), and they also produced a huge file comprised of 196 608 named RGB triplets, grouped by Color Bins.

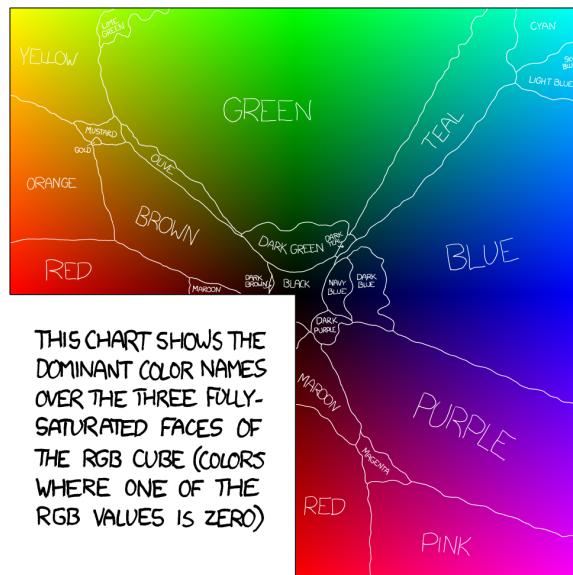


Figure 4.1: XKCD Color Survey: map of color dominant names.⁴

Despite the fact XKCD's Color Survey was not a research realized with a scientific purpose, we decided to use it since it has plenty of information available to compare our results to, 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. 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,

²XKCD - Stick-figure strip featuring humour about technology, science, mathematics and relationships, by Randall Munroe. Available at: xkcd.com/. Last accessed on September 11th, 2016.

³Color Survey Results. Available at: <https://blog.xkcd.com/2010/05/03/color-survey-results/>. Last accessed on September 11th, 2016.

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 Survey: color bins.

which could mean greater agreement to assign names to colors. These bins of color are represent with their frequencies, in table 4.2.

The idea was to compare our answers with each color bin, to create 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 lowest 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.

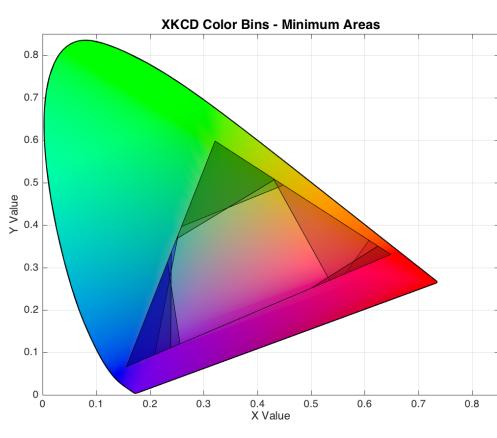


Figure 4.2: XKCD Color Survey: Color Bins Minimum Areas.

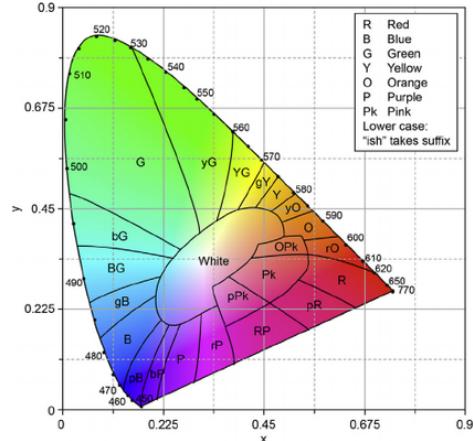


Figure 4.3: Approximate Color Regions on CIE 1931 Chromaticity Diagram. [FM97]

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 4.2), which ultimately complicates the analysis because there is more than one 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). No value was excluded from any color bin, instead we solve the problem by allowing the program to find only one of the names and look no more after finding it. 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

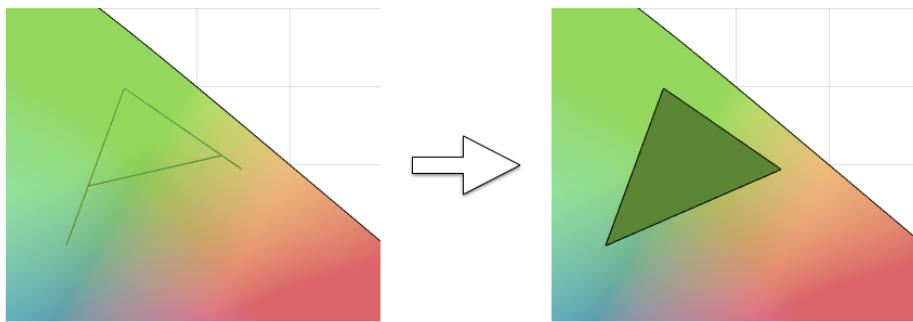


Figure 4.4: XKCD Color Survey: Color Bins Transformation from line of points, to minimum polygon.

the values are near the corner of the triangle and are distributed along two edges. The late situation is represented in Figure 4.4.

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 for identifying the colors by analyzing their values and processing the wavelength originated, comparing the resulting value with calculated areas, roughly defined by Brand Fortner [FM97] and represented on Figure 4.3. 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.

Another possible method to decode color into name 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 contained in table 4.3: 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.

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*.

By the end of this chapter, we are going to discuss the results of the analysis and consider eventual implications for Information Visualization (InfoVis) field of research.

Tables		Diagrams	
age_20_results		For each Demographic Group:	
age_20_29_results		- RGB, HSV and CMYK Responses	
age_30_39_results		- CIE-L*C*h* and L*a*b* Responses	
age_40_49_results		For Laboratory Results:	
age_50_59_results		- Regular and Daltonic Responses	
age_60_results		- RGB, HSV and CMYK Responses	
gender_female_results		- CIE-L*C*h* and L*a*b* Responses	
gender_male_results		For Online Results:	
gender_other_results		- Regular and Daltonic Responses	
lab_regular_results		- Uncalibrated Responses	
lab_daltonic_results		- RGB, HSV and CMYK Responses	
online_regular_results		- CIE-L*C*h* and L*a*b* Responses	
online_daltonic_results		For White Answers:	
online_uncalibrated_results		- White Responses	
white_answers			

Table 4.3: Generated Outputs of Data Processing Phase.

4.4.1 User Profile

As previously said on 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 along 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 informations 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 4.4 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 4.4: 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 ($\mu = 29.77$, $\bar{X}_{Age} = 23$, $\sigma = 40.30$), surprisingly having **8 users (3.09%) aged above 60 years old** which could enhance some interesting differences between age groups. Generally, our users have high 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 present 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	Nacionality						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 4.5: Results: Profiling Information (Nationalities, Countries of Residence and Languages)

The table 4.5 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 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 the users of non-industrialized countries 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 exposed 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 between zero and one ([0; 1]), since the Chromaticity Diagram has its values comprised between this interval.

In order to improve this analysis, we present Table 4.6 which contains the mean value for the distances to ideal color mixtures according to each color model: in green, it is marked the best answer for each question, in each study environment (laboratory and online).

Question ID	Presented Color	Expected Colors		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	0.10	0.11	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 4.6: Results: Distances of Results Mixed in each Color Model, for each question, with the distance from itself to the ideal pre-calculated answer. Colored in green are, the color model which has the best result, *per* question, in each environment.

As referred before, each answer pair given from our users on questions 1 to 17 (one color given, two colors asked) was blendend in 5 color models: HSV, CIE-L*C*h*, CMYK, RGB and CIE-L*a*b*. Then, the XY coordinates of each resulting mixture were mapped on a CIE Chromaticity Diagram, the centroids of each group of mixtures was calculated, and the distance from each centroid to the (ideal)

pre-calculated answer was measured. The table 4.6 represents the distance measured associated to each color model, for every laboratory result.

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. A crucial reminder is that each question set for this user study is blended in HSV Color Model: the primitives anticipated for the blends are, then, colors required to produce the result according to the HSV Color Model. The triples presented in each shaded cell of tables below, are XYZ coordinates for the CIE XYZ Color Model.

Question One This is the only question in the entire study which has yellow as the resulting color of the blending. The expected colors are Red and Green, two primitives from RGB Color Model. Table 4.7 shows the expected colors when mixing in each color model: HSV, CIE-L*C*h*, CMYK, RGB and CIE-L*a*b*.

As said before, each answer-pair was blended according to those 5 models; after processing data from each question, we performed the mean calculation over the entire set of distances, between each resulting blend and the ideal blend (according to every color model). This produced the results reported on Table 4.7.

One can observe that the model which presents the lowest mean value is the CMYK ($\tilde{x} = 0.09$), 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 ($\sigma_{lab} = 0.06$), but such value is corroborated by the online users ($\sigma_{online} = 0.06$).

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 ($\tilde{x} = 0.20$), and the values from Wilcoxon Test ($p < 0.005$) indicates that this color model has statistically significant differences every other model. **This results are corroborated by the online users.**

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

Table 4.7: Question 1, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

Question Two This question presents a Magenta color and expects to receive, from the user, the Red and Blue colors according to the HSV Color Model.

The colors were blended, and again the mean values over distances were calculated, as Table 4.8 shows. It is observable that CMYK Color Model presents, yet again, the lowest mean value for distance to ideal answer ($\tilde{x} = 0.11$), whilst its standard deviation is also the lowest between both study environments.

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 have the 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**, according to users' responses.

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.

Question ID	Given Color	Expected Colors				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)	
		\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ
Distance to Objective - Laboratory		0.22	0.13	0.16	0.09	0.11	0.06	0.17	0.11
Distance to Objective - Online		0.15	0.13	0.16	0.08	0.08	0.04	0.1	0.08
								0.16	0.08
								0.12	0.05

Table 4.8: Question 2, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

Question Three This question presents a Green color and expects to receive, from the user, the Red and Cyan colors. According to the HSV Color Model, Red and Cyan are positioned in opposite angles in the Hue Circle of Colors: therefore, blending these opposite colors that output two different colors. It is important to study to which color the users tend to blend; this question should be evaluated along with Question Four, which has the contrary output.

The colors were blended, and again the mean values over distances were calculated, as Table 4.9 shows. It is observable that CMYK Color Model presents the lowest mean value for distance to ideal answer ($\tilde{x} = 0.05$); however, the standard deviation for the HSV Color Model is the highest between both study environments ($\sigma = 0.12$).

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 CMYK has statistically different results from other color models (except RGB), therefore concluding that **CMYK has the best solution for this blending**, according to users' responses. CIE-L*C*h* is again the lower color model being significantly different from every other color model. The second best color model is **CMYK**, with statistically different results with every color model, except for **HSV**.

Once again, these results are validated by the online users' dataset. The results from this question will be useful later, when analyzing question twelve.

Question ID	Given Color	Expected Colors				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)	\tilde{x}	σ	\tilde{x}	σ
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 4.9: Question 3, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

Question Four As explained in previous question, this one is the second possible output from the blend of Red and Cyan colors. This color has no matching color pairs in the other models, since this color is only obtained in the HSV Color Model. Comparing the results for the HSV Color Model of both questions, mean distances are quite lower for question thirteen ($\tilde{x} = 0.045$), whilst the deviation of answers is higher in both questions.

Based on these results, corroborated by the online users, 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**. The results from this question can be found in table 4.10.

Question ID	Given Color	Expected Colors				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)	\tilde{x}	σ	\tilde{x}	σ
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 4.10: Question 4, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

Question Five This question expected Red and Magenta colors as response to a shade of red presented. As observed in Table 4.11, when this mixture is blended according to each color model, it generates fairly the same color.

The colors were blended, and again the mean values over distances were calculated, as Table 4.11 shows. It is observable that CMYK Color Model presents, the lowest mean value for distance to ideal answer ($\tilde{x} = 0.13$), whilst its standard deviation is also the lowest between both study environments.

However, it is not safe to say that which color model had the worst results: 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, again, 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.

Evaluating this question by the values only, it would be possible to affirm that CMYK has the best results; despite, **there is no substantial differences to declare that**, which leads us to allege that **every color model studied yield acceptable results when blending red and magenta**.

Question ID	Given Color	Expected Colors				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)	
		\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ
Distance to Objective - Laboratory		0.17	0.10	0.15	0.08	0.13	0.07	0.14	0.09
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 4.11: Question 5, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

Question Six This question expected Red and Yellow colors as response to a shade of Orange presented. As observed in Table 4.12, when this mixture is blended according to each color model, it generates fairly the same color (HSV, RGB and CMYK all generate the same shade).

The colors were blended, and again the mean values over distances were calculated, as Table 4.12 shows. It is observable that CIE-L*a*b* Color Model presents, the lowest mean value for distance to ideal answer ($\tilde{x} = 0.05$).

However, it is not safe to say that which color model had the worst results: 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 ($\tilde{x}_{CMYK} = 0.06$, $\tilde{x}_{HSV} = 0.07$ and $\tilde{x}_{RGB} = 0.08$).

The CMYK Color Model has, again, the lowest deviaton 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.

Evaluating this question by the values only, it would be possible to affirm that CIE-L*a*b* has the best results; despite, **there is no substantial differences to declare that**, since 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**.

Question ID	Given Color	Expected Colors				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)	
		\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ
Distance to Objective - Laboratory		0.07	0.10	0.13	0.09	0.06	0.06	0.08	0.09
Distance to Objective - Online		0.03	0.05	0.14	0.07	0.03	0.03	0.04	0.05
								0.05	0.07
								0.02	0.03

Table 4.12: Question 6, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

Question Seven This question expected Cyan and Magenta colors as response to Blue, presented. The range of colors generated as possible outputs from color models, varying between blue, cyan, purple and pink.

The colors were blended, and mean values over distances were calculated, as Table 4.13 shows. It is observable that CMYK Color Model proves to be again the lowest mean value for distance to ideal answer ($\tilde{x} = 0.10$), whilst offering the lowest value for deviation along with CIE-L*a*b* ($\sigma = 0.08$). CIE-L*C*h* has the highest mean result of distances, but the one which has the highest deviation is the HSV Color Model. In fact, **HSV, RGB and CIE-L*a*b* have similar**.

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, 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 4.13.

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

Table 4.13: Question 7, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

Question Eight This blending question expected Magenta and Yellow colors as response to Red presented. As observed in Table 4.14, when this mixture is blended according to each color model, it generates fairly the same color, similarly to question five.

The colors were blended, and again the mean values over distances were calculated, as Table 4.14 shows. It is observable that CMYK and HSV Color Model presents, the lowest mean value for distance to ideal answer ($\tilde{x} = 0.10$), 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 ($\tilde{x} = 0.09$), which is quite lower than the maximum value of this parameter in the online environment ($\tilde{x}_{lab} = 0.16$). 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 results: 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.

Evaluating this question by the values only, it would be possible to affirm that CMYK has the best results, due to the commitment between the mean value and standard deviation; despite, **there is no substantial differences to declare that**, which leads us to allege that **every color model studied yield acceptable results when blending magenta and yellow**, but further depth studying should be applied.

Question ID	Given Color	Expected Colors				Possible Results										
		C1	C2	HSV	CIE-L*C*h*	CMYK	RGB	CIE-L*a*b*	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ
8	(41, 21, 2)	Magenta	Yellow	(41, 21, 2)	(48, 32, 12)	(53, 38, 25)	(53, 38, 25)	(62, 51, 43)								
Distance to Objective - Laboratory		0.10	0.16	0.17	0.13	0.10	0.05	0.13	0.09	0.13	0.09	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 4.14: Question 8, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

Question Nine This blending question expected Magenta and Yellow colors as response to Red presented. As observed in Table 4.15, when this mixture is blended according to each color model, it generates fairly the same color, similarly to question five.

The colors were blended, and again the mean values over distances were calculated, as Table 4.15 shows. It is observable that CMYK and HSV Color Model presents, the lowest mean value for distance to ideal answer ($\tilde{x} = 0.10$), 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*.

Evaluating this question by the values only, it would be possible to affirm that CMYK has the best results, due to the commitment between the mean value and standard deviation; despite, **there is no substantial differences to declare that**, which leads us to allege that **every color model (except CIE-L*C*h*) studied yield acceptable results when blending green and cyan**. The results from this question will be useful when analyzing question fifteen.

Question ID	Given Color	Expected Colors				Possible Results										
		C1	C2	HSV	CIE-L*C*h*	CMYK	RGB	CIE-L*a*b*	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ
9	(40, 73, 32)	Green	Cyan	(40, 73, 32)	(44, 75, 57)	(40, 73, 32)	(40, 73, 32)	(44, 75, 44)								
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 4.15: Question 9, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

Question Ten This question presents a shade of Blue color and expects to receive, the pair Green and Magenta. As in question 3, according to the HSV Color Model, Green and Magenta are positioned in opposite angles in the Hue Circle of Colors: therefore, blending these opposite colors that output two different colors. This question should be evaluate along with Question Eleven, which has the opposite output.

These two colors, when blended, produce substantially different colors according to each model interpolation: this question could produce significantly different results from model to model, since the users would be clearly indicating which color they would tend to.

The colors were blended and the mean values over distances were calculated, as Table 4.16 shows.

It is observable that CMYK Color Model presents the lowest mean value for distance to ideal answer ($\tilde{x} = 0.013$); its standard deviation is also the lowest between both study environments ($\sigma = 0.05$), 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. The results from this question will be useful later, when analyzing question thirteen. Figures 4.5 and 4.11 demonstrates the placement of answer-pairs, and the pairs blended in HSV Color Model.

Question ID	Given Color	Expected Colors		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)	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ
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 4.16: Question 10, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

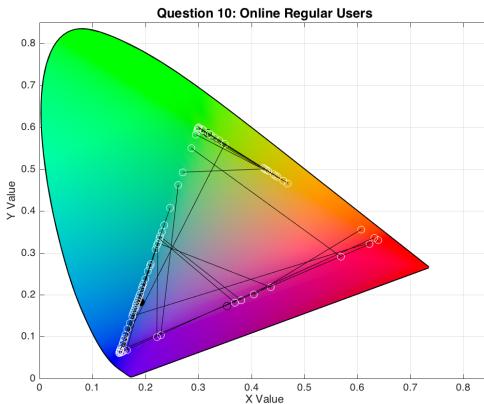


Figure 4.5: Online Results: Answers for Question 10, from regular users.

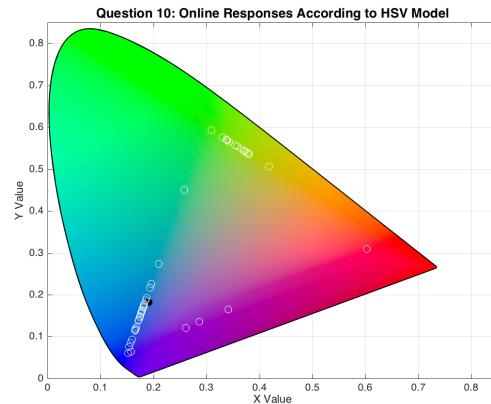


Figure 4.6: Online Results: Answers for Question 10, from regular users, mixed in HSV Color Model.

Question Eleven As explained in previous question, this one is the second possible output from the blend of Green and Magenta colors. This color has no matching color pairs in the other models, since this color is only obtained in the HSV Color Model. Comparing the results for the HSV Color Model of both questions, mean distances are dramatically lower for question fourteen ($\tilde{x} = 0.06$), whilst the deviation of answers is also lower in question fourteen.

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, corroborated by the online users, 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 4.17. These differences can be seen on Figures 4.7 and 4.8, which largely demonstrates the placement of answer-pairs, and the pairs blended in HSV Color Model.

Question ID	Given Color	Expected Colors				Possible Results											
		C1	C2	HSV	CIE-L*C*h*	CMYK	RGB	CIE-L*a*b*	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	
11	(49, 37, 5)	Green	Magenta	(49, 37, 5)	(47, 33, 4)	(21, 22, 24)	(21, 22, 24)	(47, 48, 41)									
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 4.17: Question 11, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

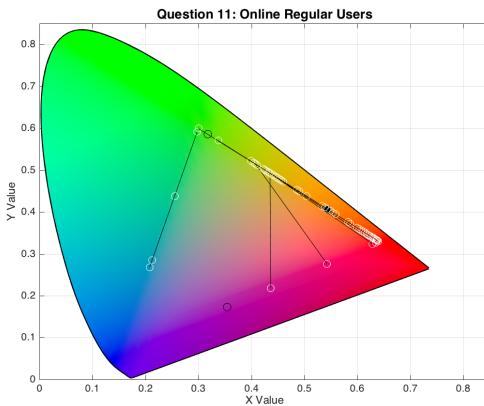


Figure 4.7: Online Results: Answers for Question 11, from regular users.

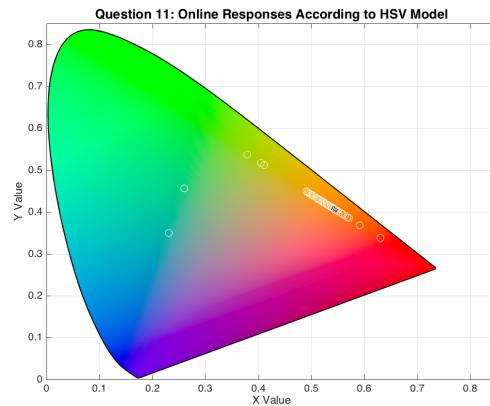


Figure 4.8: Online Results: Answers for Question 11, from regular users, mixed in HSV Color Model.

Question Twelve This blending question expected Green and Yellow colors as response to a tone of **Green** presented. This green tone is equal to the one presented in question three, therefore its results are interesting to compare with this question. As observed in Table 4.18, when this mixture is blended according to each color model, it generates almost the same green color, so distances and their statistics are expected to be closer to each other.

The colors were blended, and again the mean values over distances were calculated, as Table 4.18 shows. It is observable that HSV Color Model presents, the lowest mean value for distance to ideal answer ($\tilde{x} = 0.11$), whilst standard deviation for the CMYK Color Model provides the lowest value between both study environments ($\sigma_{lab} = 0.04$, $\sigma_{online} = 0.05$).

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. 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 4.9 and 4.10 compare the results from both question three and twelve, blended in HSV (the model which yields the best results).

Question ID	Given Color	Expected Colors				Possible Results										
		C1	C2	HSV	CIE-L*C*h*	CMYK	RGB	CIE-L*a*b*	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ
12	(45, 76, 12)	Green	Yellow	(45, 76, 12)	(54, 81, 13)	(45, 76, 12)	(45, 76, 12)	(53, 81, 13)	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ
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 4.18: Question 12, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

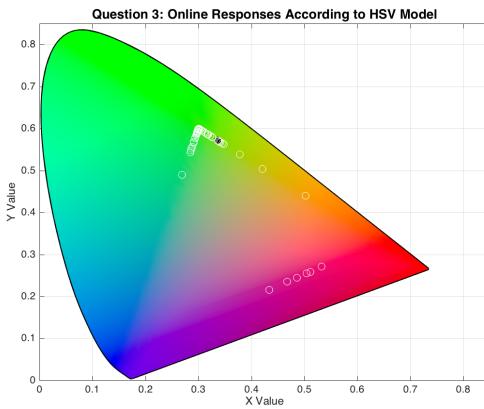


Figure 4.9: Online Results: Answers for Question 3, from regular users, mixed in HSV Color Model.

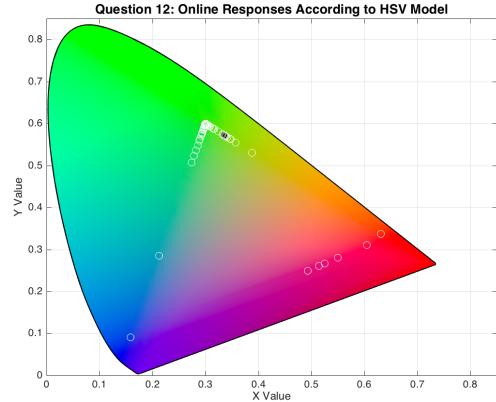


Figure 4.10: Online Results: Answers for Question 12, from regular users, mixed in HSV Color Model.

Question Thirteen This mixture expected in this question contains Blue and Cyan colors as response to a lighter tone of **Blue**, which was presented. Similar to previous question, this one had presented a repeated color: this blue shade is equal to the one presented in question ten, therefore its results are interesting to compare with this question. As observed in Table 4.19, when this mixture is blended according to each color model it generates similar colors, except for CIE-L*C*h* that has a higher blending than others.

The colors were blended, mean values over distances calculated, as Table 4.19 shows. 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, this results are not consistent with the online users, which indicated responses closer to the RGB Color Model ($\sigma_{online} = 0.13$).

Analyzing the laboratory results, it shows HSV is the worst-generating values Color Model, having the higher mean value ($\tilde{x}_{HSV} = 0.27$) 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*.

The fact that online users' data indicate a slight tendency to the RGB Color Model, could be justified as **the blue color is a primitive of such color model, making it easier to map against a mental model of color.**

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 is 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 4.11 and ?? compare the results from both question three and twelve, blended in HSV and RGB respectively, (the model which yielded the best results in each question).

Question ID	Given Color	Expected Colors				Possible Results											
		C1	C2	HSV	CIE-L*C*h*	CMYK	RGB	CIE-L*a*b*	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	
13	(26, 23, 98)	Blue	Cyan	(26, 23, 98)	(33, 37, 100)	(26, 23, 98)	(26, 23, 98)	(32, 30, 99)									
		\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ		
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 4.19: Question 13, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

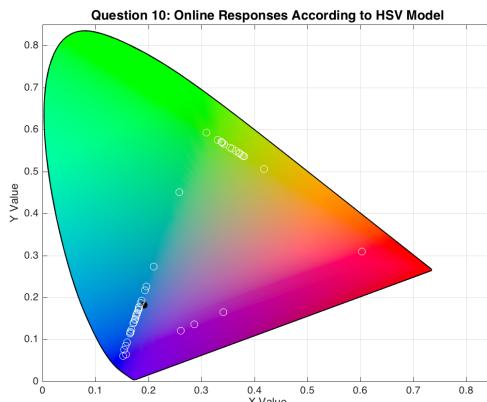


Figure 4.11: Online Results: Answers for Question 10, from regular users, mixed in HSV Color Model.

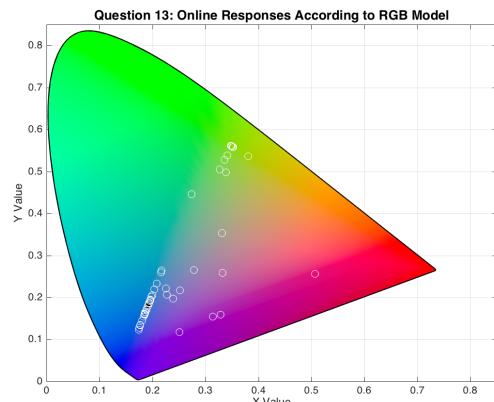


Figure 4.12: Online Results: Answers for Question 13, from regular users, mixed in RGB Color Model.

Question Fourteen This blending question expected Blue and Magenta colors as response to a resulting color of **Purple** (presented to the user). As in Table 4.20, when this mixture is blended according to each color model, it generates fairly the same color (precisely the same between HSV, RGB and CMYK).

The colors were blended, and again the mean values over distances were calculated, as Table 4.20 shows. It is observable that CMYK Color Model presents, the lowest mean value for distance to ideal answer ($\tilde{x} = 0.10$ laboratory, and $\tilde{x} = 0.09$ 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 ($\tilde{x} = 0.30$). 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*.

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**.

Question ID	Given Color	Expected Colors				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)	
		\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ
Distance to Objective - Laboratory		0.12	0.14	0.30	0.09	0.10	0.05	0.13	0.13
Distance to Objective - Online		0.10	0.12	0.29	0.13	0.09	0.05	0.11	0.12
								0.13	0.09

Table 4.20: Question 14, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

Question Fifteen This question presents a shade of Green color and expects to receive, the pair Blue and Yellow. According to the HSV Color Model, Blue and Yellow are positioned in opposite angles in the Hue Circle of Colors: therefore, blending these opposite colors that output two different colors. This question should be evaluate along with Question Sixteen, which has the opposite output. 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.

These two colors, when blended, produce substantially different colors according to each model interpolation: this question could produce significantly different results from model to model, since the users would be clearly indicating which color they would tend to.

The colors were blended and the mean values over distances were calculated, as Table 4.21 shows. It is observable that CMYK Color Model presents the lowest mean value for distance to ideal answer ($\tilde{x} = 0.06$); its standard deviation is also the lowest between both study environments ($\sigma = 0.03$). 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 greener the shade. **This value, in fact, sustains the result of HSV Color** ($\tilde{x}_{HSV} = 0.09$), 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 4.13 and 4.14 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**, according to users' responses. It is necessary to analyze pairwise the next question to evaluate the effectiveness of this output, for Blue and Yellow colors blending.

Question ID	Given Color	Expected Colors		Possible Results														
		C1	C2	HSV		CIE-L*a*b*		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)	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ
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 4.21: Question 15, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

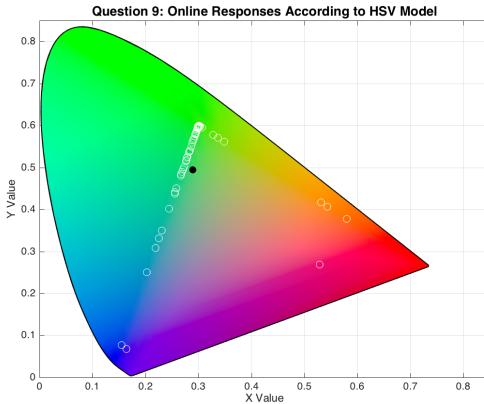


Figure 4.13: Online Results: Answers for Question 9, from regular users, mixed in HSV Color Model.

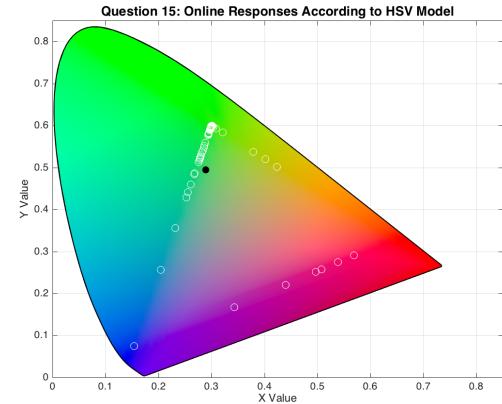


Figure 4.14: Online Results: Answers for Question 15, from regular users, mixed in HSV Color Model.

Question Sixteen As explained in previous question, this one is the second possible output from the blend of Blue and Yellow colors. This color has no matching color pairs in the other models, since this color is only obtained in the HSV Color Model. Comparing the results for the HSV Color Model of both questions, mean distances are largely high for question sixteen ($\tilde{x}_{lab} = 0.21$, $\tilde{x}_{online} = 0.19$), whilst the deviation of answers is also lower in question fifteen.

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, 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 4.22. These differences can be seen on Figures 4.15 and 4.16, which largely demonstrates the placement of answer-pairs, and the pairs blended in HSV Color Model.

Question ID	Given Color	Expected Colors		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)	
		\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ
Distance to Objective - Laboratory		0.21	0.10	0.22	0.12	0.10	0.05	0.16	0.07
Distance to Objective - Online		0.19	0.12	0.17	0.09	0.10	0.06	0.15	0.07
								0.12	0.08
								0.11	0.06

Table 4.22: Question 16, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

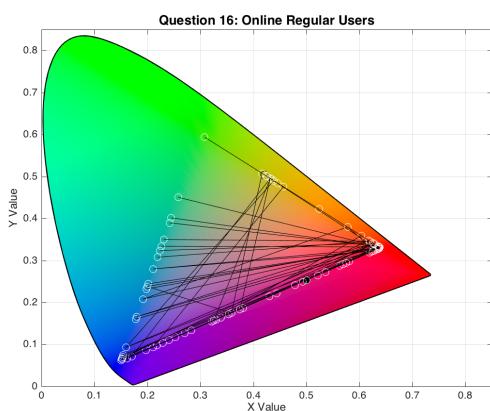


Figure 4.15: Online Results: Answers for Question 16, from regular users.

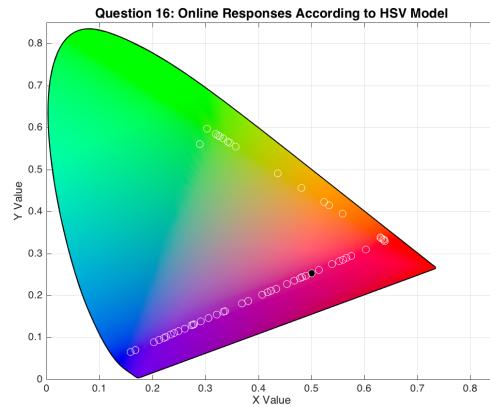


Figure 4.16: Online Results: Answers for Question 16, from regular users, mixed in HSV Color Model.

Question Seventeen The last question in which we ask the user to indicate two colors is this: we expected to receive Cyan and Yellow colors as response, to a resulting color of **Green** (presented to the user). As in Table 4.23, when this mixture is blended according to each color model, it generates fairly the same color (precisely the same between RGB and CMYK).

The colors were blended, and mean values over distances were calculated. It is observable that CMYK Color Model presents the lowest mean value for distance to ideal answer ($\tilde{x} = 0.05$ laboratory, and $\tilde{x} = 0.05$ 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 ($\tilde{x} = 0.16$), 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.

Evaluating this question, it is possible to affirm that **CMYK has the best results when cyan and yellow**, due to the commitment between the mean value and standard deviation, 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**.

Question ID	Given Color	Expected Colors				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)	\tilde{x}	σ								
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 4.23: Question 17, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

Question ID	HSV		CIE-L*C*h*		CMYK		RGB		CIE-L*a*b*	
	Mean (\tilde{x})	Std-Dev (σ)	Mean (\tilde{x})	Std-Dev (σ)	Mean (\tilde{x})	Std-Dev (σ)	Mean (\tilde{x})	Std-Dev (σ)	Mean (\tilde{x})	Std-Dev (σ)
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 4.24: Laboratory Results: Statistics for distances *per* question, of Results Mixed in each Color Model, for each question. In Green/Red shade, the three best/worst results for each descriptive statistic.

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. Based on table 4.6, which presents the mean values for each color model decomposed by question, we can run descriptive statistics over its column and produce table 4.25 that is going to be helpful when inspecting the results *per* color model. We have also 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 condensed in table 4.24.

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

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.

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 (\bar{x})	0.14	0.20	0.10	0.14	0.14	0.11	0.20	0.09	0.12	0.13
Std-Dev (σ)	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	0.26	0.17	0.14	0.17	0.18	0.14	0.21	0.11	0.16	0.20
Variance (σ^2)	0.006	0.003	0.001	0.002	0.002	0.002	0.004	0.001	0.002	0.003

Table 4.25: Condensed Statistics for Distances to Ideal Results, mixed in each Color Model. In Green/Red shade, the best/worst result for each descriptive statistic.

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; it is also one of the color models which has the lowest ranges of values on the same environment, which could indicate greater agreement between distances to the ideal HSV Color Model answer.

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). The mean values distances for this questions were $\tilde{x}_{11} = 0.0587$, $\tilde{x}_{17} = 0.0683$ and $\tilde{x}_6 = 0.0741$. On the other hand, we consider 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 $\tilde{x}_2 = 0.2173$, $\tilde{x}_{13} = 0.2713$ and $\tilde{x}_{10} = 0.3$.

By analyzing table 4.25, we can conclude that the HSV color model is the one which has a wider range of distances (laboratory environment) compared to other models: this could be due to the fact that **the color sliders which were in the user study, presented a color scale with the spectrum of hues from the HSV Color Model.**

When comparing the results from the HSV 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 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°) 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 4.17). 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

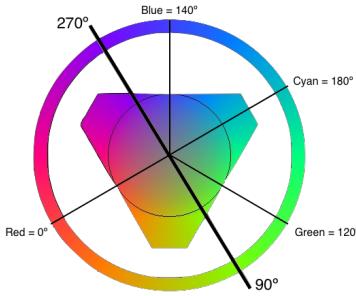


Figure 4.17: Example of HSV Hue Circle, with opposed hue values. Depicted: Questions 3 and 4, with resulting hues 270° and 90° .

results: they are both a bit far from the expected colors ($\tilde{x}_{distance-3} = 0.0941$ and $\tilde{x}_{HSV-4} = 0.1162$), although the mean distance to the HSV precalculated 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. Green & Magenta Blend - Unlike the previous blend, the results between these questions were quite different between each other concerning the distance to the expected colors: $\tilde{x}_{HSV-10} = 0.3$ and $\tilde{x}_{HSV-11} = 0.0587$. 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 $\tilde{x}_{distanceC1-C2} = 0.645$, which is largely different from the expected colors. 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. Blue & Yellow Blend - 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 ($\tilde{x}_{HSV-15} = 0.09$, $\sigma_{HSV-15} = 0.03559$); 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 4.18, 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 expected colors is $\tilde{x}_{HSV-16} = 0.2087$ and the standard deviation for the distances of answers blended in HSV is $\sigma_{HSV-16} = 0.10378$. 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**.

Another interesting example is Question ten and thirteen: they both present a shade of blue, which could be obtained by two strands, 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 ($\tilde{x}_{HSV-10} = 0.3$, $\sigma_{HSV-10} = 0.15792$) when compared to the standard deviation of the whole model ($\sigma_{HSV} = 0.08$). These results are, thus, consistent with the known fact [COLOCAR REF] 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 4.20 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

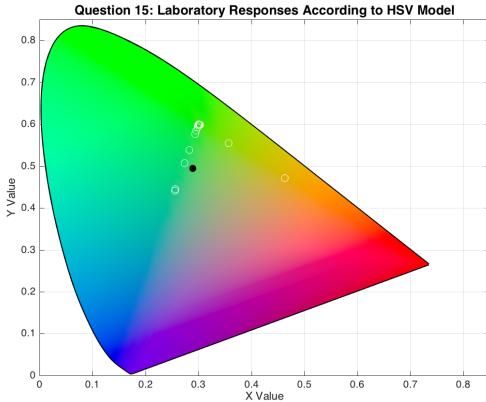


Figure 4.18: Laboratory Results: Answers for Question 15, from regular users, mixed in HSV Color Model.

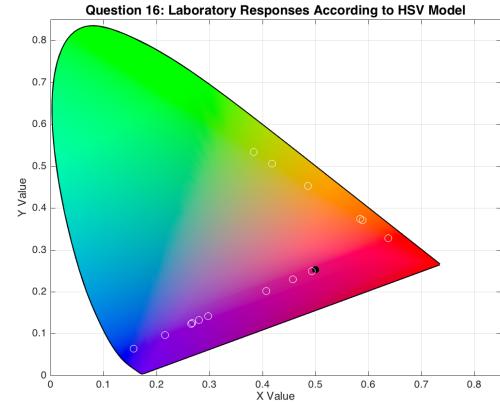


Figure 4.19: Laboratory Results: Answers for Question 16, from regular users, mixed in HSV Color Model.

the ideal HSV Color Model response, while is accompanied by the range of values which compose its answers.

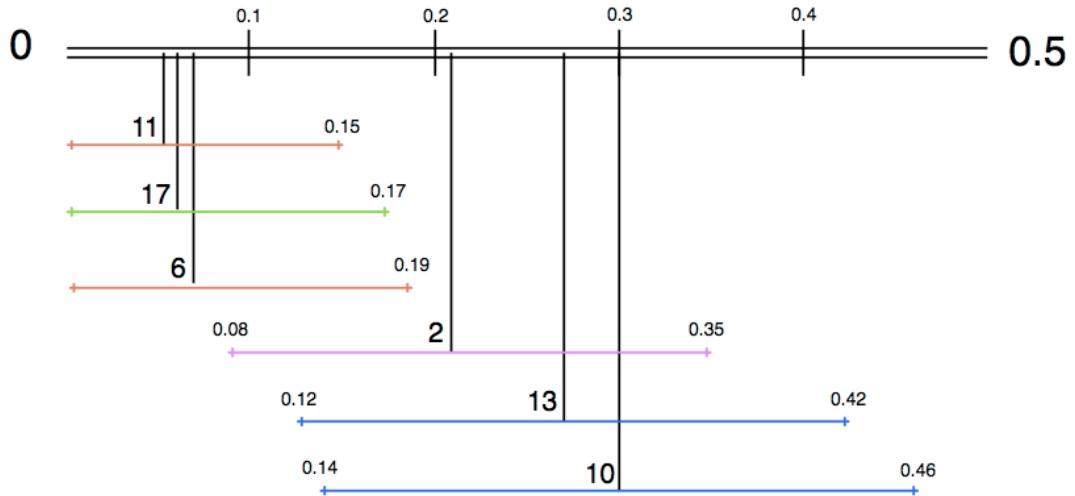


Figure 4.20: Best and Worst Questions, according to HSV Color Model.

CIE-L*C*h* Color Model Blendings 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 4.25: it has the highest mean value on laboratory and online environment, and the highest standard deviation, range and variance exclusively on the online environment. These results are consistent with the individual questions' values, seen before this section.

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 $\tilde{x}_6 = 0.1332$, $\tilde{x}_5 = 0.15$ and $\tilde{x}_2 = 0.1573$ 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 $\tilde{x}_{10} = 0.2557$, $\tilde{x}_{14} = 0.2995$ and $\tilde{x}_{15} = 0.3031$. 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 ($\tilde{x}_{10} = 0.2557$) and deviation ($\sigma_{10} = 0.1164$) values, strengthening the theory that **blue shades and tones will probably yield worst results, due to the fact that it is the color which humans have less descriptive power**.

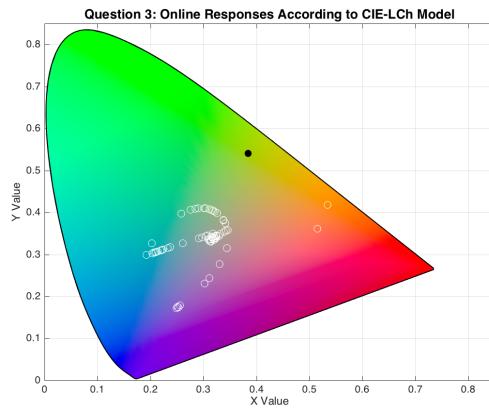


Figure 4.21: Online Results: Answers for Question 3, from regular users, mixed in CIE-L*C*h* Color Model.

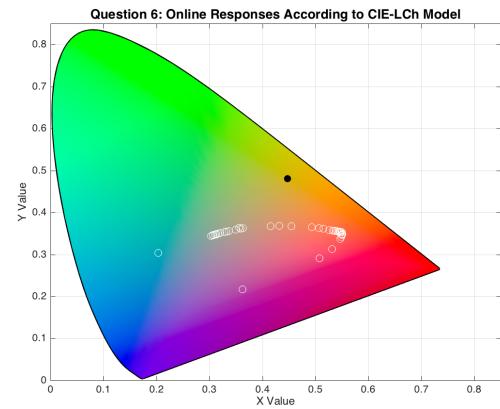


Figure 4.22: Online Results: Answers for Question 6, from regular users, mixed in CIE-L*C*h* Color Model.

The question which revealed one of the lowest standard deviation value (meaning less oscillation of results), relating the online environment, was question three ($\sigma_3 = 0.05855$): this question help us illustrate the difference between each of the descriptive statistics, since it has one of the highest mean value of distances ($\tilde{x}_{17} = 0.23$) 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 4.21.

The question which has the lowest mean value of distances was question six ($\sigma_{LCh-6} = 0.1332$), and it is represented on Figure 4.22. 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 4.23 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 CIE-L*C*h* Color Model response, while is accompanied by the range of values which compose its answers.

CMYK Color Model Blendings The CMYK Color Model is, by far, the one which presents the best results for most of the descriptive statistics present on Table 4.25, being authenticated by the results from the online environment: it has the lowest mean value of distances ($\tilde{x}_{lab} = 0.10$, $\tilde{x}_{online} = 0.09$),

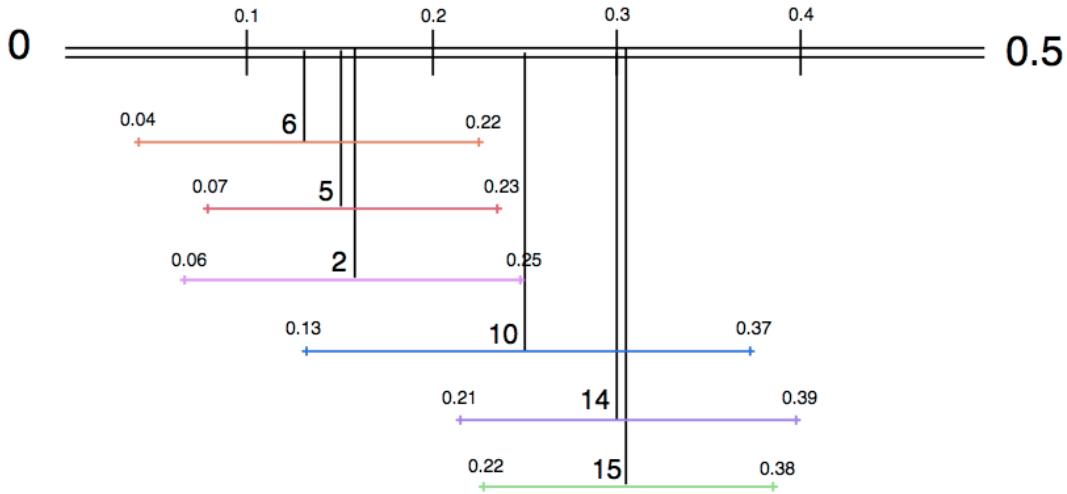


Figure 4.23: Best and Worst Questions, according to CIE-L*C*h* Color Model.

lowest standard deviation ($\sigma_{lab} = 0.04$, $\sigma_{online} = 0.04$), the lowest range of values ($range_{lab} = 0.14$, $range_{online} = 0.11$) and, finally, the lowest variance value ($\sigma_{lab}^2 = 0.001$, $\sigma_{online}^2 = 0.001$).

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 $\tilde{x}_{17} = 0.0452$, $\tilde{x}_6 = 0.0577$ and $\tilde{x}_{15} = 0.0625$ which, contrary to the previous color model, are all values below 0.1, 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 $\tilde{x}_{10-12} = 0.1314$, $\tilde{x}_5 = 0.1322$ and $\tilde{x}_{13} = 0.1875$. 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 ($\tilde{x}_{13} = 0.1875$, $\sigma_{13} = 0.13097$), 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 coherent 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 Red, Yellow, Blue (RYB) and CMYK Color Models without even knowing it.

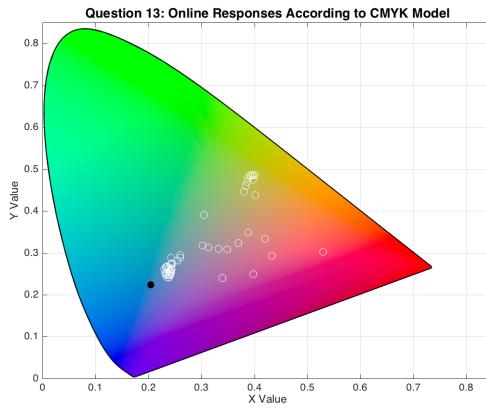


Figure 4.24: Online Results: Answers for Question 13, from regular users, mixed in CMYK Color Model.

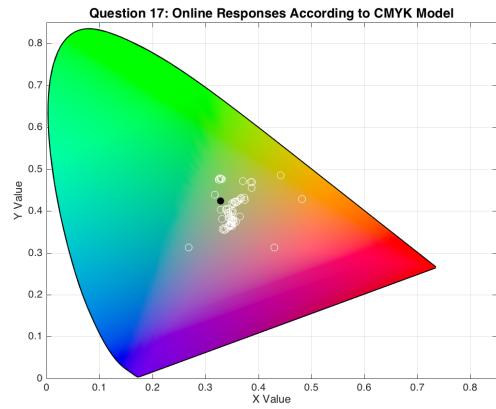


Figure 4.25: Online Results: Answers for Question 17, from regular users, mixed in CMYK Color Model.

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 4.24 represents the results of Question 13, which had wider distances to the pre-calculated CMYK blend, and Figure 4.25 show the results for Question 17, the question with closer 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. 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.

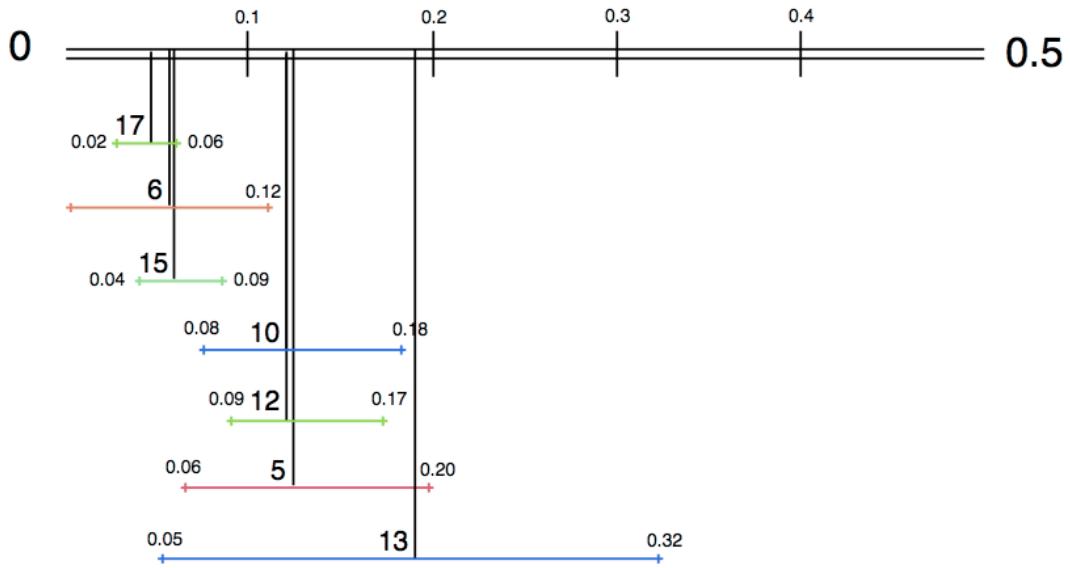


Figure 4.26: Best and Worst Questions, according to CMYK Color Model.

RGB Color Model Blendings 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 4.25, authenticated by the results from the online environment, prove RGB has one of the lowest mean value of distances ($\tilde{x}_{lab} = 0.14$, $\tilde{x}_{online} = 0.12$) and one of the lowest standard deviations ($\sigma_{lab} = 0.05$, $\sigma_{online} = 0.04$ equal to $\sigma_{CMYK-online}$).

The three questions which have shorter distances are 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 $\tilde{x}_6 = 0.0777$, $\tilde{x}_9 = 0.1005$ and $\tilde{x}_{17} = 0.1030$.

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 $\tilde{x}_2 = 0.1660$, $\tilde{x}_{10} = 0.2107$ and $\tilde{x}_{13} = 0.2450$. 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.**

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 the majority of questions (ten questions), while presenting statistically significant differences with CMYK in thirteen 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 (e.g. RGB) or subtractive ones (e.g. CMYK)**.

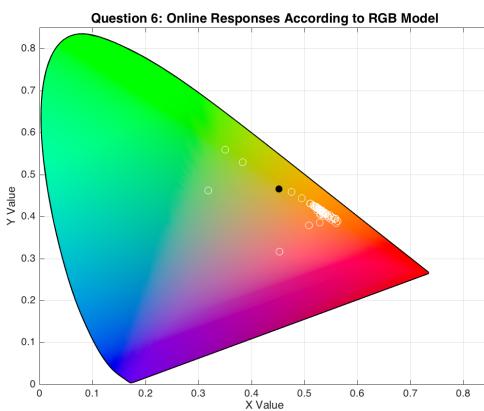


Figure 4.27: Online Results: Answers for Question 6, from regular users, mixed in RGB Color Model.

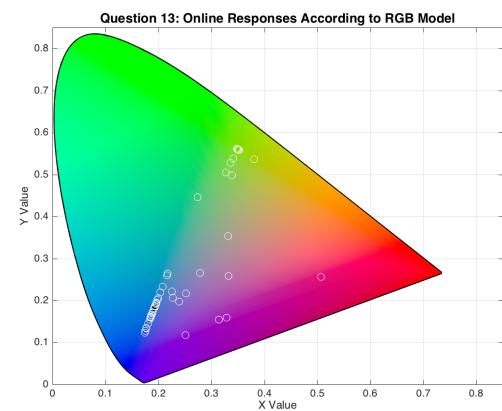


Figure 4.28: Online Results: Answers for Question 13, from regular users, mixed in RGB Color Model.

Figure 4.27 represents the results of Question 6, which had the shortest distances to the pre-calculated RGB blend, and Figure 4.28 show the results for Question 13, the question with wider distances. 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.

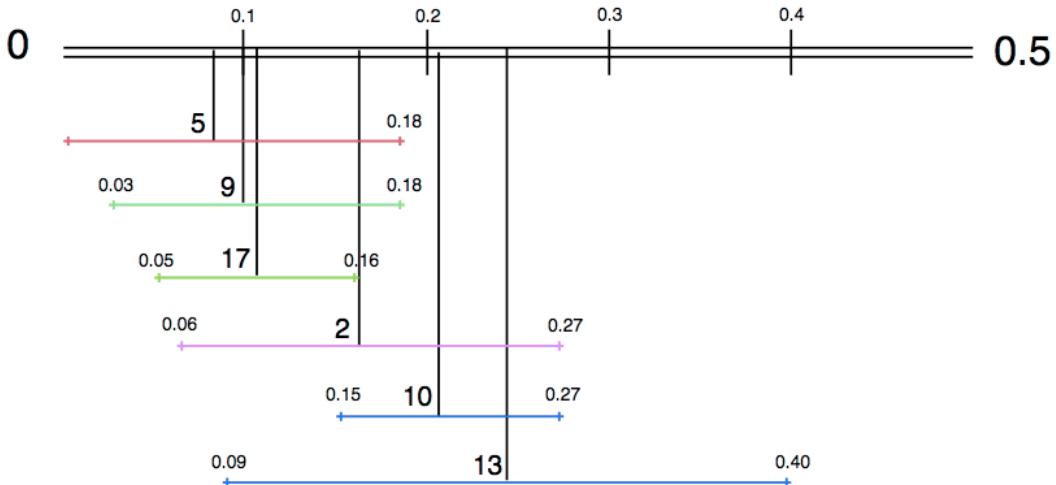


Figure 4.29: Best and Worst Questions, according to RGB Color Model.

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 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 $\tilde{x}_6 = 0.0509$, $\tilde{x}_{17} = 0.1130$ and $\tilde{x}_9 = 0.1142$.

Considerint 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 $\tilde{x}_{12} = 0.1743$, $\tilde{x}_{10} = 0.2107$ and $\tilde{x}_{13} = 0.2450$. 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 4.30 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 4.31 shows the results for the same question, but the online results which confirm the laboratory ones. The diagram of Figure 4.32 contains the three top and bottom-valued questions, disposed on top of an interval [0; 0.5] of differences.

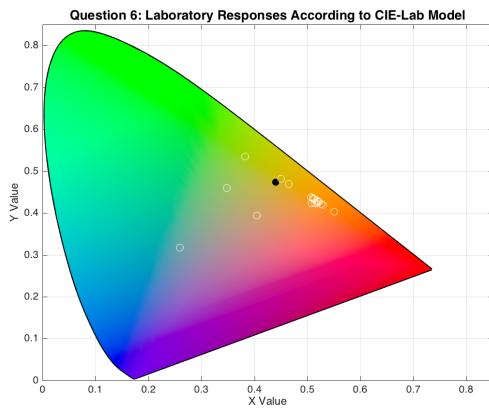


Figure 4.30: Laboratory Results: Answers for Question 6, from regular users, mixed in CIE-L*a*b* Color Model.

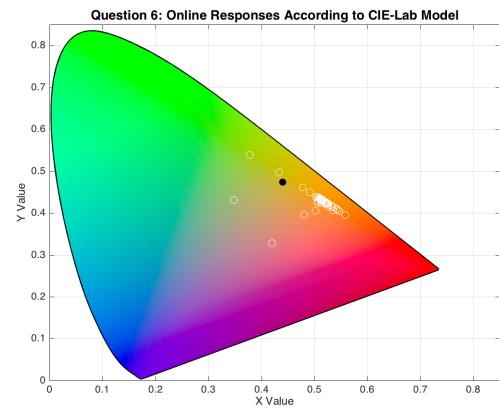


Figure 4.31: Online Results: Answers for Question 6, from regular users, mixed in CIE-L*a*b* Color Model.

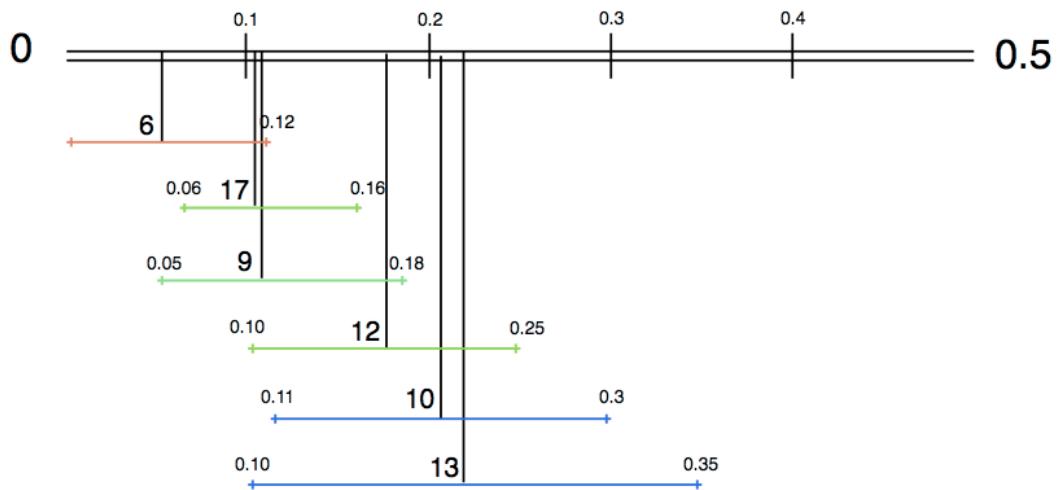


Figure 4.32: Best and Worst Questions, according to CIE-L*a*b* Color Model.

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 4.26, with cells shaded in green which represent the best value for each one of questions.

Question ID	Presented Colors		Expected Color	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 4.26: 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. Colored in green are, the color model which has the best result, *per question*, in each environment.

As seen on the table, the results are roughly similar to the ones found on Table 4.24, which depicted 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.

Question ID	Presented Colors		Expected Color	Possible Results										
	C1	C2		HSV	CIE-L*C*h	CMYK	RGB	CIE-L*a*b*	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ
20	Green	Blue	(54, 79, 107)	(54, 79, 107)	(32, 34, 100)	(12, 17, 23)	(12, 17, 23)	(26, 28, 40)	\tilde{x}	σ	\tilde{x}	σ	\tilde{x}	σ
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 4.27: Question 20, with expected colors, possible results, mean and standard deviation of distances to Objective colors.

- 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 4.27; as seen, the color model which has the closest ideal result is the CIE-L*a*b* ($\tilde{x}_{lab} = 0.11$, $\tilde{x}_{online} = 0.10$), 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 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 4.33

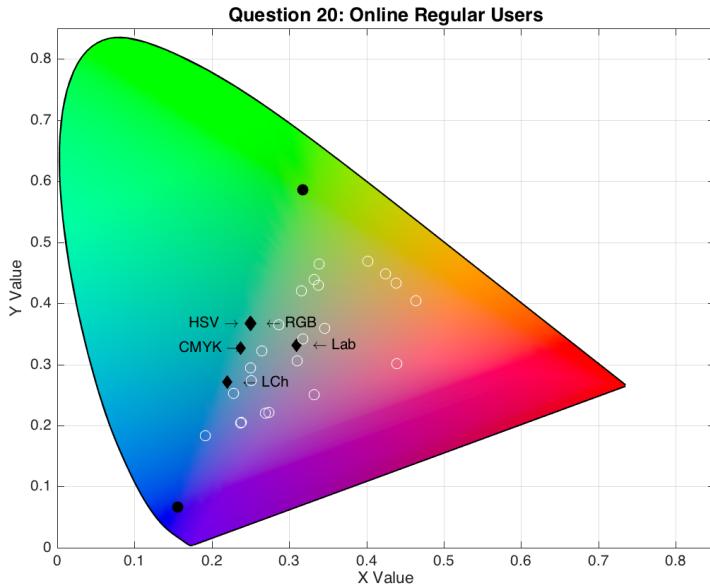


Figure 4.33: Online Results: Answers for Question 20, from regular users.

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.

- Distances - Comparing the mean distances obtained previously on Table 4.25 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 ($\tilde{x}_{HSV} = 0.18$, $\tilde{x}_{CMYK} = 0.13$).
Blending Cyan and Yellow to produce green is an example of a question which had one a higher value ($\tilde{x}_{Green=Cyan+Yellow} = 0.11$) when asked the user to indicate the blending-basis with sub-sequential 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 ($\tilde{x}_{Cyan+Yellow=Green} = 0.05$); this example if pictured in Figures 4.34 and 4.35.
- 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 indicate 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 great 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

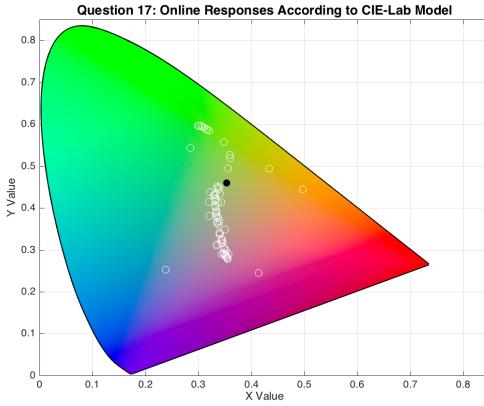


Figure 4.34: Online Results: Answers for Question 17, from regular users, mixed in CIE-L*a*b* Color Model.

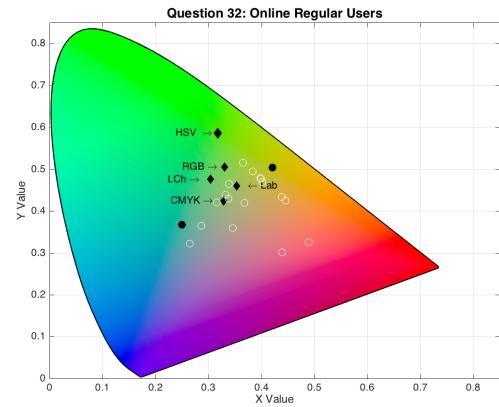


Figure 4.35: Online Results: Answers for Question 32, from regular users.

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 4.24. However, as seen on Table 4.28, 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 (\bar{x})	Online (\bar{x})	Laboratory (\bar{x})	Online (\bar{x})	Laboratory (\bar{x})	Online (\bar{x})	Laboratory (\bar{x})	Online (\bar{x})	Laboratory (\bar{x})	Online (\bar{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 4.28: 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 (4.29) 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 ($\tilde{x}_{HSV} = 0.18$) while the one which has the shortest mean distance value continues to be CMYK, along with CIE-L*a*b* ($\tilde{x} = 0.13$)**. 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 ($\sigma = 0.07$), the highest range of distances ($range = 0.22$) and the

highest variance of values ($\sigma^2 = 0.005$), 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 (\bar{x})	0.18	0.17	0.13	0.14	0.13	0.17	0.15	0.11	0.13	0.12
Std-Dev (σ)	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 (σ^2)	0.003	0.005	0.002	0.001	0.002	0.004	0.005	0.002	0.001	0.002

Table 4.29: 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 4.30. 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; marked in **bold** are the color models which we have concluded to yield the best results, according to each type of question asked.

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	#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*	CMYK	CIE-L*a*b*	RGB	CIE-L*C*h*	CMYK
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*	CMYK	CIE-L*a*b*	CIE-L*a*b*	CIE-L*C*h*	CMYK
Green	Blue	(54, 79, 107)	-				CIE-L*a*b*		HSV, RGB		CMYK				CMYK	CIE-L*C*h*	
Red	Cyan	(45, 76, 12) (27, 12, 95)	CMYK	HSV	RGB	CIE-L*a*b*	CIE-L*C*h*	RGB	CMYK	CIE-L*a*b*	HSV	CIE-L*C*h*	CMYK	CIE-L*a*b*	HSV	CIE-L*C*h*	CMYK
Red	Magenta	(45, 23, 22)	CMYK	CIE-L*a*b*	RGB	CIE-L*C*h*	HSV	HSV	CIE-L*C*h*, CIE-L*a*b*	RGB	CIE-L*a*b*	CIE-L*C*h*	CMYK	CIE-L*a*b*	RGB	CMYK	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				HSV	RGB	
Cyan	Magenta	(18, 7, 95)		Inconclusive Results					CMYK, CIE-L*a*b*		CIE-L*C*h*		RGB		HSV		
Magenta	Yellow	(41, 21, 2)	CMYK	CIE-L*C*h*	HSV	RGB	CIE-L*a*b*	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) (49, 37, 5)	CMYK	RGB	CIE-L*a*b*	HSV	CIE-L*C*h*	RGB	CMYK	CIE-L*a*b*	HSV	CIE-L*C*h*	CMYK	CIE-L*a*b*	HSV	CIE-L*C*h*	CMYK
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	CIE-L*a*b*	CIE-L*C*h*	CMYK	CIE-L*a*b*	RGB	HSV	CMYK
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	CIE-L*a*b*	CIE-L*C*h*	CMYK	RGB	HSV		
Blue	Yellow	(40, 73, 32) (45, 23, 22)	CMYK	RGB	HSV	CIE-L*a*b*	CIE-L*C*h*	CMYK	RGB	HSV	CIE-L*a*b*	CIE-L*C*h*	CMYK	CIE-L*a*b*	CIE-L*C*h*	CMYK	CMYK
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 4.30: 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 proposed to the user, there were 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 were created, as in other questions, by blending the primitives of the most common color models (RGB and CMYK) which, ultimately, happen to provide the primary colors which formulate the ones referred in the beginning of this paragraph. These questions (**primary colors, formulated based on other primary colors**) are refreshed again on Table 4.31.

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 4.31: 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 que mixture-basis, since they all tend to present better results when blended according to a CMYK Color Model. However, we have found an interesting behaviour from our users when answering these questions: some users indicated the resulting color on both the expected colors (e.g. it was presented Red, 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 4.31, 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 demonstrate 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 ($\bar{x} = 0.49$, $\sigma = 0.25$) 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 4.36 and 4.37 show us the answers given by the online users in, respectively, question eight and twenty-five.

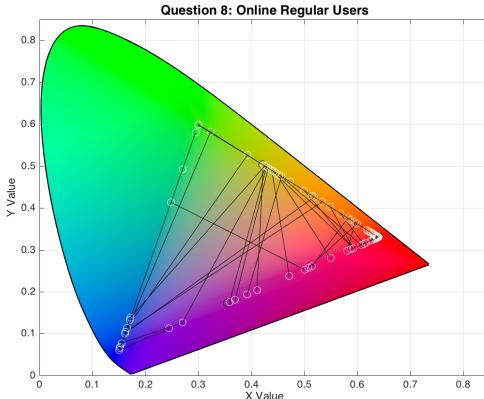


Figure 4.36: Online Results: Answers for Question 8, from regular users.

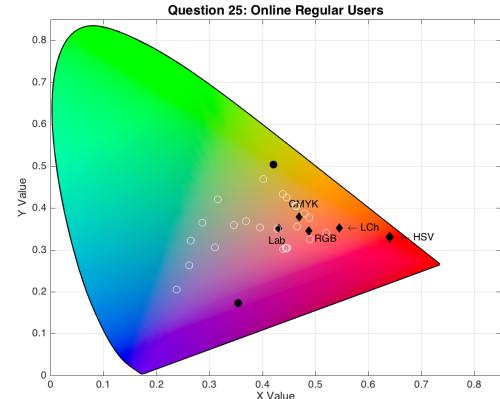


Figure 4.37: Online Results: Answers for Question 25, from regular users.

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 4.38.

Additionaly, 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 ($\bar{x} = 0.40$, $\sigma = 0.21$) 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 4.39 and 4.39 show us the answers given by the online users in, respectively, question seventeen and thirty-two.

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 4.40 and 4.41 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.

Running some descriptive statistics on top of the distance values between the given answers and the expected Cyan-Magenta Pair ($\bar{x} = 0.45$, $\sigma = 0.11$) 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**

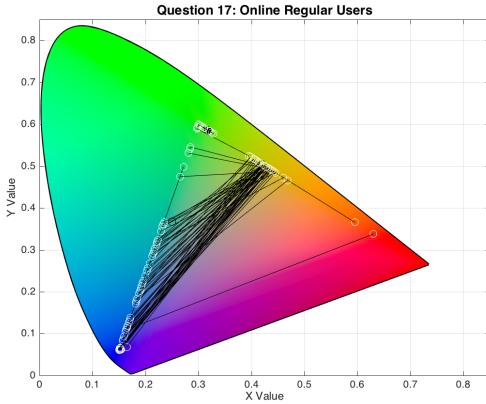


Figure 4.38: Online Results: Answers for Question 17, from regular users.

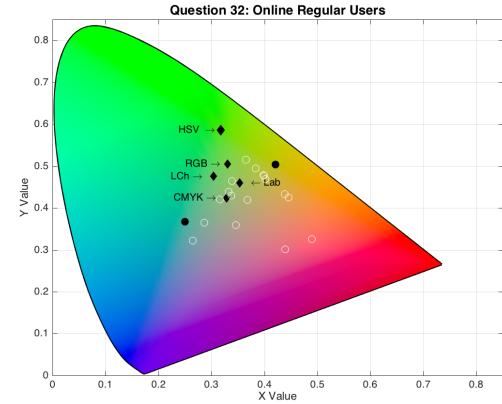


Figure 4.39: Online Results: Answers for Question 32, from regular users.

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**.

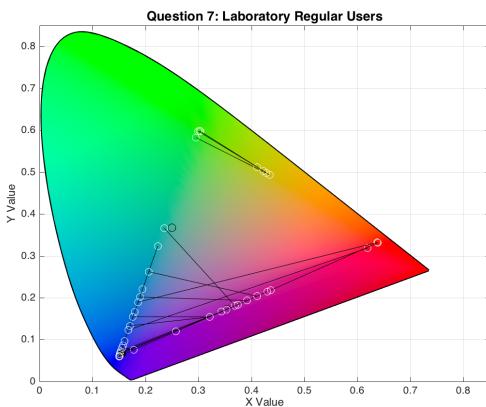


Figure 4.40: Laboratory Results: Answers for Question 7, from regular users.

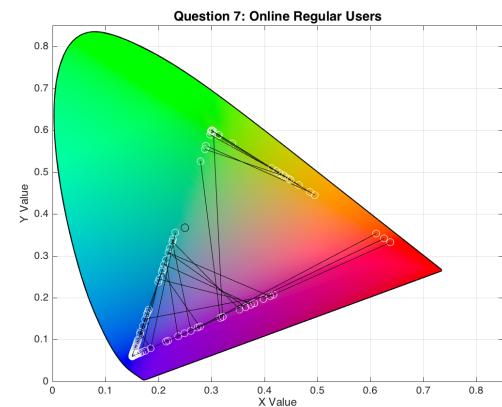


Figure 4.41: Online Results: Answers for Question 7, from regular users.

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 ($\tilde{x} = 0.13$, $\sigma = 0.06$) reveals some proximity to the expected color, 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 4.42 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 ($\tilde{x} = 0.53$, $\sigma = 0.36$) 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 coherent 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.

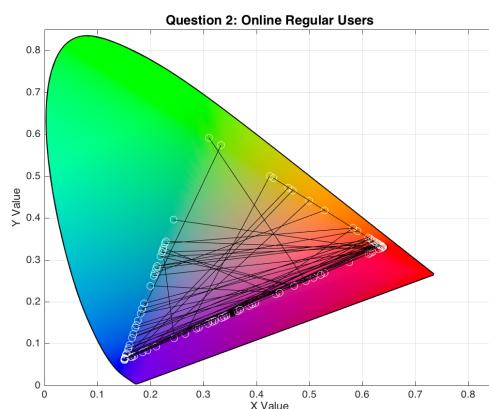


Figure 4.42: Online Results: Answers for Question 2, from regular users.

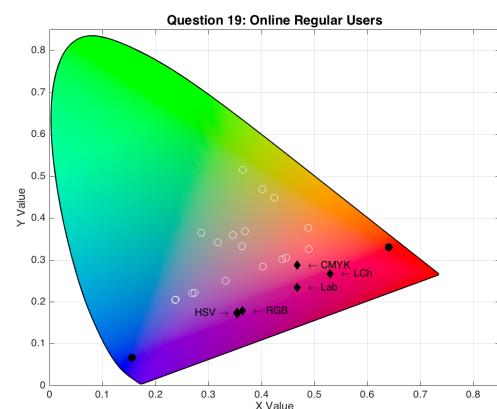


Figure 4.43: Online Results: Answers for Question 19, from regular users.

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 4.44.

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 ($\bar{x} = 0.41$, $\sigma = 0.22$) 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 understanding 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.

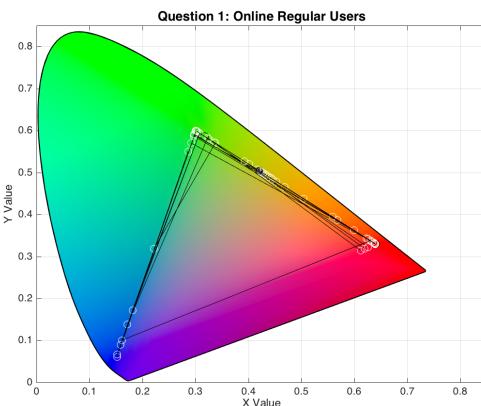


Figure 4.44: Online Results: Answers for Question 1, from regular users.

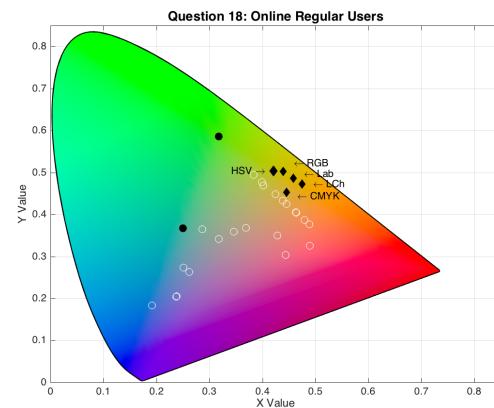


Figure 4.45: Online Results: Answers for Question 18, from regular users.

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 4.32, 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).

				Given the Result, Asked for Basis						Given the Basis, Asked for the Result					
Blending Basis		Blending Result		Laboratory			Online			Laboratory			Online		
C1	C2	C3		Mean (\bar{x})	Std-Dev (σ)	Mode (M_o)	Mean (\bar{x})	Std-Dev (σ)	Mode (M_o)	Mean (\bar{x})	Std-Dev (σ)	Mode (M_o)	Mean (\bar{x})	Std-Dev (σ)	Mode (M_o)
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	
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							
Green	Yellow	(49, 37, 5)	4.17	0.887	5	2.06	1.035	5	2.68	1.16	3	2.25	1.17	2	
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	
Cyan	Yellow	(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 4.32: Color Blending Effort, according to users' answers.

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 effor 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 two and three between one and 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**. These results are confirmed by the online responses, by running a Friedman 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** (sixty-three entries), **Red-Green, producing Yellow** (sixty entries) and **Blue-Yellow, producing a Pink shade** (fifty-six entries); the ones which had less were **Red-Yellow, producing a Orange shade** (twenty-six entries), **Green-Yellow, producing a Lime-Green color** (twenty-four entries) and **Blue-Magenta, producing a Purple shade** (twenty 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 4.46 and 4.47 all represent the set of answer-pairs with one white component, for questions one, ten and fifteen, respectively.

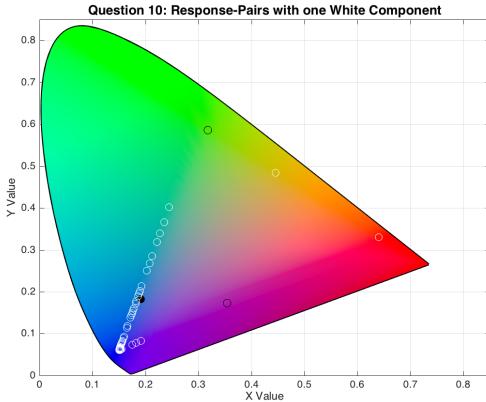


Figure 4.46: Answer-pairs with one white component, from Question 10.

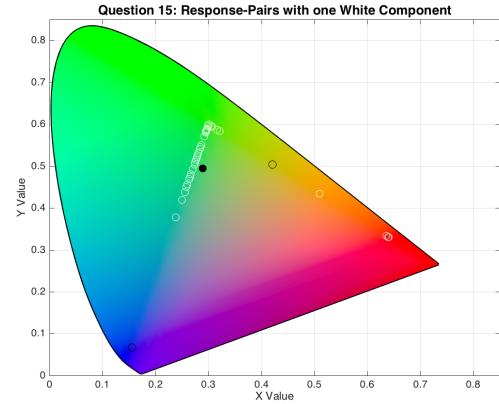


Figure 4.47: Answer-pairs with one white component, from Question 15.

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 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.

Additionaly, 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 perfom an additional informal evaluation of the results collected from color vision deficient users.

Age Groups

Recalling Table 4.4, 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 runned 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 4.48 and 4.49 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.

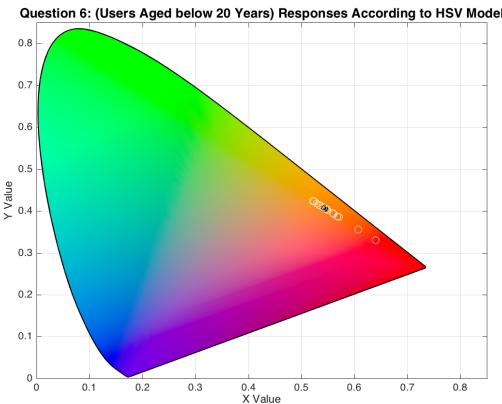


Figure 4.48: Demographic Results, from Question 6, for answers given by users aged below 20 years, blended according to HSV Color Model.



Figure 4.49: Demographic Results, from Question 6, for answers given by users aged between 40 and 49 years, blended according to HSV Color Model.

Gender Groups

Recalling Table 4.4, 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 ($\rho < 0.05$).

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 runned 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 4.50 and 4.51 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.

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

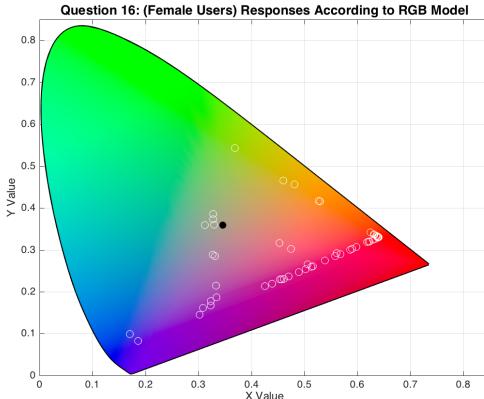


Figure 4.50: Demographic Results, from Question 16, for answers given by female users, blended according to RGB Color Model.

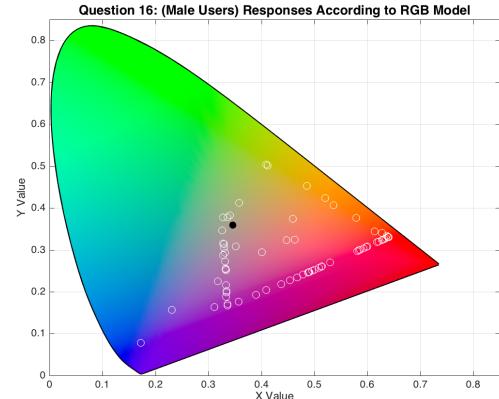


Figure 4.51: Demographic Results, from Question 16, for answers given by male users, blended according to RGB Color Model.

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 ranging 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 observed on Figures 4.52 and 4.53. 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 2.5, of Section 2.1.2).

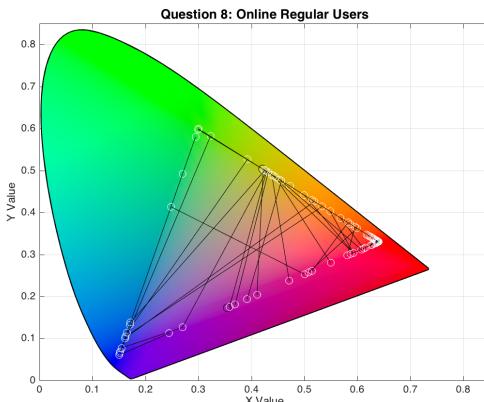


Figure 4.52: Online Results: Answers for Question 8, from regular users.

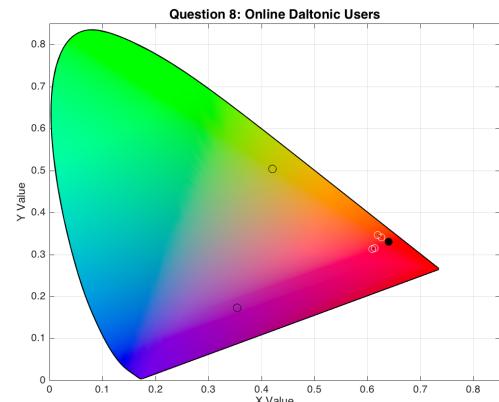


Figure 4.53: Online Results: Answers for Question 8, from daltonic users.

Cyan + Yellow = Green On the other hand, when we presented one of the blenders 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 environments 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 4.54 and 4.55 help us supporting this explanation.

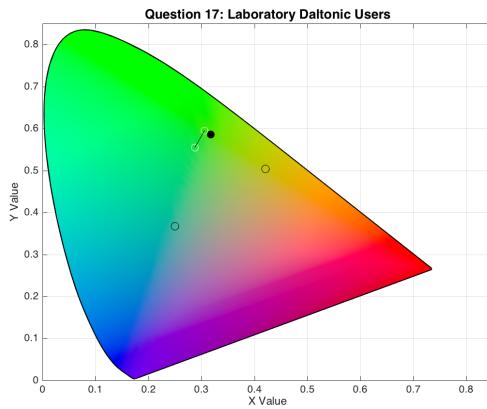


Figure 4.54: Laboratory Results: Answers for Question 17, from daltonic users.

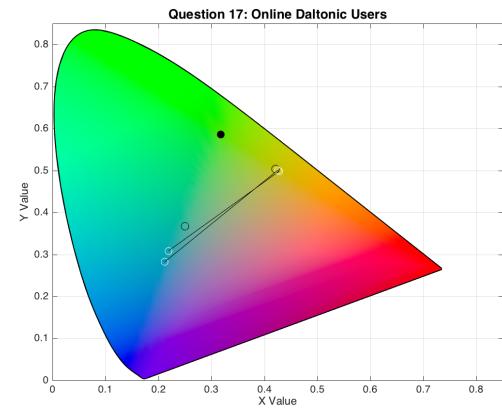


Figure 4.55: Online Results: Answers for Question 17, from daltonic users.

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

Fazer apanhado dos resultados todos.

Responder a perguntas levantadas.

abordar questão de que modelos originaram melhores respostas, se são aditivos ou subtrativos.

Referir que é preciso estudos para perceber de facto qual é o melhor entre o HSV, Lab e RGB.

CMYK claramente melhor

LCh claramente pior.

4.5.1 Calibration Resiliency

Como verificamos ainda alguns users com calibração imprópria para teste, considerámos que poderia ser uma fonte de resultados interessantes. Como tal, criámos um dataset para os mesmos e comparámos com os resultados dos utilizadores calibrados. Os resultados são os que se seguem...

4.5.2 Creation of Color Scales

Aproveitar resultado de respostas em branco

4.5.3 Color Organization

Falar da conclusão de $A + B = C (=) C = A + B$?

4.5.4 Implications for InfoVis

Resumo dos resultados todos e regras que se podem levar deste trabalho para a área de InfoVis em geral.

Chapter 5

Conclusion

5.1 Limitations

Most of the data cleaning would be avoided if the collected were saved in a different fashion (NONEs, HSL)...

5.2 Future Work

Software de calibração remota.

Bibliography

- [AM03] National Imagery Agency and Mapping. International Code of Signals 1969 Edition, 2003.
- [Att54] Fred Attneave. Some Informational Aspects of Visual Perception. *Psychological Review*, 61(3):183–193, 1954.
- [Chi14] Mazviita Chirimutu. The Metaphysical Significance of Colour Categorization. In *Colour Studies: a Broad Spectrum*, pages 1–29. Anderson, Biggam, Hough & Kay (eds.), 2014.
- [CSKH90] Christine A. Curcio, Kenneth R. Sloan, Robert E. Kalina, and Anita E. Hendrickson. Human photoreceptor topography. *The Journal of comparative neurology*, 292(4):497–523, 1990.
- [dAK92] Dilogen de Alwis and Chee Kon. A new way to use the ishihara test. *Journal of Neurology*, 239(8):451–454, 1992.
- [FM97] Brand Fortner and Theodore E. Meyer. *Number by Colors*. Springer-Verlag New York, 1 edition, 1997.
- [GC04] N. Gossett and Baoquan Chen. Paint inspired color mixing and compositing for visualization. In *Information Visualization, 2004. INFOVIS 2004. IEEE Symposium on*, pages 113–118, 2004.
- [GG14a] Sandra Gama and Daniel Gonçalves. Studying the perception of color components' relative amounts in blended colors. In *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational*, NordiCHI '14, pages 1015–1018, New York, NY, USA, 2014. ACM.
- [GG14b] Sandra Gama and Daniel Gonçalves. Studying Color Blending Perception for Data Visualization. In N. Elmqvist, M. Hlawitschka, and J. Kennedy, editors, *EuroVis - Short Papers*. The Eurographics Association, 2014.
- [GJH11] Paula Ginter, Joan Jones, and Syed Hoda. True colors. *International journal of surgical pathology*, 19(4):494–496, 2011.
- [Goe10] Johann Goethe. Theory of Colours. XXXIII, 1810.
- [HB10] Jeffrey Heer and Michael Bostock. Crowdsourcing graphical perception: Using mechanical turk to assess visualization design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '10, pages 203–212, New York, NY, USA, 2010. ACM.
- [Hum39] David Hume. *A Treatise of Human Nature*. Oxford University Press, 2000 [1739].
- [Ish72] Shinobu Ishihara. *The Series of Plates Designed as a Tests for Colour-Blindness, 24 Plates Edition*. Kanehara Shuppan Co. Ltd., 1972.

- [JG78] George H. Joblove and Donald Greenberg. Color spaces for computer graphics. In *Proceedings of the 5th Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '78, pages 20–25, New York, NY, USA, 1978. ACM.
- [Lev96] Haim Levkowitz. Perceptual steps along color scales. *International Journal of Imaging Systems and Technology*, 7(2):97–101, 1996.
- [LH13] Sharon Lin and Pat Hanrahan. Modeling how people extract color themes from images. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, pages 3101–3110, New York, NY, USA, 2013. ACM.
- [MFHL02] Nathan Moroney, Mark Fairchild, Robert Hunt, and Changjun Li. The ciecam02 color appearance model. *Color and Imaging Conference*, 2002(1):23–27, 2002.
- [Mun19] Albert Henry Munsell. *A Color Notation*. New York, Munsell Color Co., 1919.
- [Nat68] Convention On Road Signs and Signals. pages 1–61, Vienna, Austria, November 1968. United Nations.
- [Rhe00] Penny L. Rheingans. Task-based color scale design. In *In Proceedings Applied Image and Pattern Recognition. SPIE*, volume 3905, pages 35–43, May 2000.
- [War] Colin Ware. Morgan Kaufmann Publishers Inc., second edition.
- [You02] Thomas Young. The bakerian lecture: On the theory of light and colours. *Philosophical Transactions of the Royal Society of London*, 92:12–48, 1802.

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 your 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 Deficiencies 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

Your new appendix chapter's content goes here

Appendix C

Chromaticity Diagrams

Include Diagrams generated of CIE Horseshoe.

Appendix D

Tables

D.1 Results Tables

Users

Um exemplo de uma tabela de resultados raw

Um exemplo de uma tabela de resultados clean

Um exemplo de uma tabela de calibração