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Color Tolerances in Vehicle Design

Master's Thesis in Industrial Design Engineering

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Master's thesis in Industrial and Materials Science (IMSX30)
Color Tolerances in Vehicle Design
Thesis in collaboration with the Perceived Quality attribute department within Volvo Cars Corporation

Cover image: Illustration of car interior with various color swatches below
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Abstract

This study explores customer's perception of interior color tolerances in vehicles, with the aim of understanding how small color variations can impact their satisfaction of the vehicle's appearance. The study also set out to investigate and give recommendations on how to design for a more forgiving appearance regarding color variances in vehicle interiors.

To begin, extensive literature studies were performed to gain a greater understanding of color theory and the current state of research on color tolerances and how they affect customers' perceptions. Based on the findings, a user study was designed to investigate customers' preferences for color tolerances on interior components of a vehicle. The user study comprised recruiting a diverse group of participants and presenting them with various color combination plaques, which were composed of a master plaque that represented the "correct" color and a variation plaque with a slight color difference. Participants were then asked to give their opinion for each combination. A group of color experts also participated in the user tests, acting as a reference point for the study.

The collected data underwent analysis to identify trends and patterns in customers' preferences. The results indicate that the participants in the study are more accepting than the tolerance limits used by the automotive company discussed in this report, suggesting that current requirements may need to be revised.

Design recommendations were created to provide an understanding of how to design for a more forgiving appearance regarding color variation in vehicles. These guidelines were developed by leveraging insights gained from color theory and the analysis of the user studies and interviews conducted with experts in the field of color and vehicle design. The resulting recommendations are expected to provide automotive designers with information that can aid in the development of vehicle interiors which allow a satisfactory appearance despite some degree of color variation between components.

The findings indicate that a more forgiving appearance can be achieved by incorporating transition details between two different materials, which can make color differences between them more acceptable. Additionally, such details can serve as a visual focus, detracting attention from any color differences. Another crucial design recommendation is to embrace greater color variation instead of uniformity, as this will also contribute to a more forgiving appearance. However, this should be done with caution as to not create an unharmonious appearance. Furthermore, materials that possess greater structural complexity can be more accommodating towards greater color tolerances. Lastly, careful consideration should be given to the selection of colors. This is largely because the eye's sensitivity to differences in hue depends on where the color is located in the color sphere.

In conclusion, this master thesis report presents a comprehensive investigation of interior color tolerances in the context of the automotive industry. The study findings provide valuable insights into customer preferences which can aid in regulation of color tolerances and design of vehicle interiors which ensures that customers' expectations are satisfied.

Acknowledgements

This Master's thesis has been conducted in collaboration with Perceived Quality attribute department at Volvo Cars. The project would not have been possible without the unwavering support from the supervisors who have been responsible for the project, both at Chalmers and at Volvo Cars.

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Alvina Ståhl Hanna Murgård

Glossary

The glossary provides a comprehensive list of specialized terms, acronyms, and abbreviations used throughout the thesis. It includes concise definitions and explanations of these terms, enabling readers to better understand the specific concepts and language used in the study. By providing a clear and accessible reference to technical language, the glossary enhances the reader's ability to engage with the research and comprehend its findings.

A: A common reference illuminant used in color measurement and calibration.

CIELAB: A color space used to describe color differences and perceived color. Colors are located within a three-dimensional rectangular coordinate system; the three dimensions are lightness (L*), redness/greenness (a*) and yellowness/blueness (b*).

CIELCH: A polar-coordinate version of CIELAB, where L* represents lightness, C* represents chroma, and H* represents hue.

Chroma: The purity or intensity of a color, often used synonymously with saturation.

D65: A standardized daylight illuminant used in color measurement and calibration.

Δa* (or Da): The color difference along the a* axis in CIELAB color space.

Δb* (or Db): The color difference along the b* axis in CIELAB color space.

ΔC* (or DC): The color difference in chroma between two colors in CIELCH color space

ΔH* (or DH): The color difference in hue between two colors in CIELCH color space.

ΔL* (or DL): The color difference in lightness between two colors in CIELAB/CIELCH color space.

F2: A fluorescent light source used as a reference illuminant in color measurement and calibration.

Hue: The attribute of a color that distinguishes it from other colors and is described by terms such as red, blue, or green.

Master plaque: A reference color standard used in color measurement and calibration.

PQ: The Perceived Quality attribute department at Volvo Cars. It is responsible for assuring that customers are satisfied with the overall quality of the vehicles by establishing various requirements.

SCI: Spectral component included, a measurement mode that includes both specular and diffuse reflection in color measurement.

SCE: Spectral component excluded, a measurement mode that excludes specular reflection in color measurement.

ΔE: The total color difference between two colors, often calculated as the Euclidean distance in CIELAB or CIELCH color space between two colors.

VCC: Volvo Cars Corporation.

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INTRODUCTION

This master thesis project is a collaboration between two master students at Chalmers University of Technology and the Perceived Quality attribute department at Volvo Cars. In this chapter, the project is introduced by explaining the background to why it is being conducted, as well as the aim of the project and its demarcations.

1.1. Background

In the automotive industry, color tolerances have always been essential in ensuring consistency and quality in the production of components such as seats, dashboard, and door panels. Setting appropriate color tolerances is essential since any deviation from the standard can affect the appearance of the vehicle and negatively impact customer satisfaction. Automotive manufacturers strive to ensure that the color of each vehicle is consistent and matches the desired standard color as closely as possible. However, the emergence of more sustainable materials such as mechanically recycled plastics and bio-based polymers can make it more challenging to adhere to current tolerance limits due to variations in material properties.

The automotive industry is a continuously evolving sector that constantly embraces advancements in technology, materials, and design. As new materials, finishes, and manufacturing techniques emerge, there is a continuous need to update color tolerance limits to ensure that vehicles meet the evolving standards and customer expectations. As current requirements may need to be revised, there is a need for research to be conducted in order to determine customers perception of color differences, as well as to identify their preferred color tolerance limits.

Furthermore, to create appearances which allow a greater variation in color without compromising customer satisfaction, automotive designers need to be increasingly aware of how to tackle these problems. It involves selecting materials and colors that can work together harmoniously, maintaining visual appeal and brand identity while still ensuring consistency and sustainability.

In conclusion, there is a growing need to understand customers' view of interior color tolerances to develop more sustainable materials that meet their expectations. There is also a need to inform automotive designers on how to handle the issues of greater color variations in vehicles. To investigate these matters and provide automotive manufacturers with relevant recommendations, this master thesis project was initiated.

1.2. Purpose and aim

The thesis is motivated by the growing use of sustainable materials in the automotive industry, which has led to increased complexity in meeting existing color tolerances. As a result, it is imperative to revisit the current requirements and ensure that they are aligned with the latest trends and practices in the industry.

While it may be necessary to reassess current requirements, challenges arise in locating relevant research on customer acceptance of interior color tolerances within the automotive industry. This scarcity of information can likely be attributed to its classification as proprietary knowledge. With this in mind, the primary objective of the thesis is to undertake an in-depth investigation of customer requirements in regard to interior color tolerances.

This thesis work aims specifically at investigating color variation and acceptable color tolerance levels for interior components in cars from a customer's perspective. It also aims to explore possible solutions for how to design in a more forgiving way regarding color variations in the interior of a car.

Research questions:

- How can requirements regarding color tolerances in interior car components be modeled so that they correspond to the customers' expectations?
- How can we design vehicle interiors in a way that allows a more forgiving combination of color variants?

1.3. Demarcations

The study will not take into consideration the potential effect of aging on the selected materials. This is an important aspect to keep in mind, as materials can change in appearance over time due to exposure to various environmental factors such as sunlight, moisture, and temperature fluctuations. While aging effects could potentially impact color tolerance, the focus of this study is specifically to investigate materials in their newest, non-aged, condition.

Additionally, it is worth noting that this study will only be examining the interior components of cars. While the exterior of a vehicle can also be subject to color-related tolerance issues, this study will not explore those aspects.

Lastly, the study will be investigating two specific colors: Charcoal Solid and Dawn. Charcoal Solid is a dark grey/black color and Dawn is a light beige color. These two colors were selected based on their prevalence in car interiors. By focusing on just two colors, the study can more effectively target potential issues and provide relevant recommendations for addressing them.

1.4. Thesis outline

This thesis report aims to investigate color tolerances in vehicle design and creating design recommendations which can help make interior vehicle design more forgiving towards color differences. The report is divided into eight chapters, beginning with an introduction that provides the background and purpose of the study, as well as the demarcations. The second chapter outlines the theoretical framework, covering topics such as human color perception, color measurement, and tolerance limits. Chapter three focuses on the execution of the study, detailing the process map, the selected colors and plaques, and the development of a method for measuring color tolerances. User studies are described in detail, including the test setup, plaque comparison, and sources of error. Chapter four presents the results and analysis, including scatter charts with tolerance limits and new color tolerance recommendations. Chapter five offers design recommendations based on the findings, while chapter six provides a discussion of the results and their implications. The report concludes with chapter seven, which summarizes the study's conclusions and offers recommendations for future work, and chapter eight with a reference list of sources cited throughout the report.

2

THEORETICAL FRAMEWORK

This chapter delves into the theoretical foundation that underpins the research project. It serves to provide a comprehensive understanding of the key theoretical concepts and frameworks that are relevant to the research questions and methodology employed in the study. Through an exploration of relevant literature, this chapter seeks to establish a clear theoretical framework that will inform the subsequent analysis and interpretation of the data.

2.1. Chapter structure

This chapter presents the theoretical framework that underpins the study. It is divided into several sections that cover the different aspects related to the study of color in the automotive industry.

Section 2.2 provides an in-depth description of the theoretical background related to color**.**

Section 2.3 focuses on the tolerance limits and tolerances that are commonly used in the automotive industry.

In **Section 2.4**, the content centers on standardized light sources and measurement tools, which are essential in achieving accurate color matching.

Section 2.5 provides insights into the color master plaque and its significance in visual assessment.

Finally, **Section 2.6** delves into the details of user studies, which are conducted to evaluate customers' requirements on color tolerances.

2.2. Theoretical background on color

This section presents a comprehensive theoretical background on several crucial aspects related to color. It explores the intricate subjects of human color perception, color measurement, the impact of material characteristics on color, color variation, and color vision testing.

Human color perception

In order to examine colors, there are three things which must be present: a light source (illuminant), an object (sample), and an observer/processor. The human eye and brain work together to translate light into color. As light hits an object, the material will absorb specific wavelengths. The wavelengths that aren't absorbed get reflected. This reflected light travels into the eye to the retina, which is covered with millions of light receptive cells called rods and cones. When these cells detect light, they send signals to the brain which makes us perceive the reflecting object as being a particular color (Pantone, n.d.).

How a color is perceived and interpreted is highly subjective. Different factors like eye fatigue, age, and environment influences color perception (X-Rite, n.d.). Also, personal preferences can affect each person's color perception, and the communication of colors can differ greatly between people. For example, women tend to have a broader color description language than men. As explained by Fider and Komarova (2019), this is mainly because women have significantly more color-related hobbies than men.

According to research, females show less saturation loss than males in the greenish regions of the color space (Fider & Komarova, 2019). Furthermore, about 8% of men and 1% of women have some type of color impairment. The most common impairment is red and green dichromatism which makes it difficult to tell apart red and green colors. However, most people with color deficiencies are not aware that they might perceive colors differently than others (Pantone, n.d.).

A colors appearance is based on three elements: hue, chroma (or saturation) and value (lightness). By using these three attributes every color can accurately be identified and distinguished from each other, (X-Rite, n.d.).

Hue

The hue is how an object's color is perceived, for example red, orange, green, blue, etc. In Figure 1 a color sphere shows the continuum of color from one hue to the next, (X-Rite, n.d.).

Chroma

The chroma describes how close the color is to either gray or pure hue, in other words the vividness or dullness of a color. As seen in Figure 1 on the color sphere, the colors in the center are more gray (dull) and become more and more saturated (vivid) the further out it gets. Another word for chroma is saturation, (X-Rite, n.d.).

Value

A colors degree of lightness is called value. When comparing colors value, they can be described as light or dark (X-Rite, n.d.). In Figure 1, the three-dimensional color sphere depicts color lightness on its vertical axis, showing the lightest values at the top and the darkest values at the bottom.

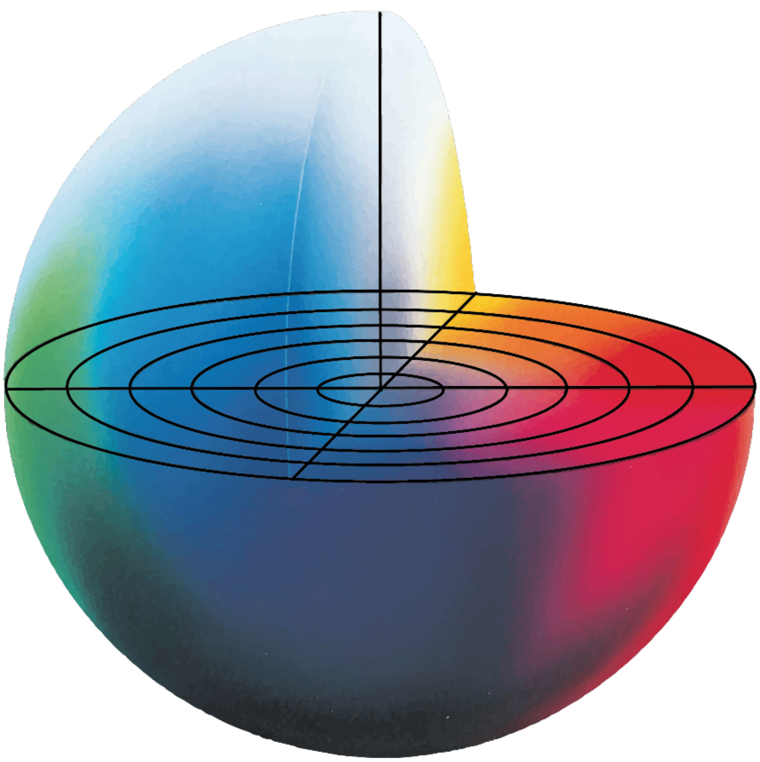


Figure 1, Color sphere

Color measurement

Research has shown that visual methods of color comparison and color determination are subjective while measurements using instruments are objective, ("A Method for Evaluating Human Observer's Perception of Color Differences," 2021).

A spectrophotometer is a device that measures spectral transmittance, spectral reflectance, or relative spectral emittance. It is the most commonly used instrument for measuring color but there are other options, for example a colorimeter, (X-Rite, n.d.). In order for instruments to see color, three things are needed: a light source, an object and an observer/processor. Color measurement instruments perceive color the same way humans do, by gathering and filtering the wavelengths of light reflected from an object. The instrument perceives the reflected light wavelengths as numeric values, (X-Rite, n.d.).

Color can be measured in two ways, either with "True color measurement" or with "Perceived color measurement". To measure the true color of an item, all the reflected light must be captured regardless of the reflection angle. This is called Specular Component Included (SCI). To measure the perceived color of an item, the specular component (which usually is the dominant type of reflection) is excluded. This is done to make the result more sensitive to scattered light caused by the surface conditions, such as gloss and texture. This type of measurement is called Specular Component Excluded (SCE). The perceived color may be different from the same true color measured depending on position of the observer due to specular angle of reflection from the light source and its surrounding, reflection from the ground or adjacent objects (Micomlab, n.d.). The perceived color can also be influenced by the material properties of the object.

The International Commission on Illumination (CIE), also known as the Commission Internationale de l'Eclairage, is tasked with creating international recommendations for the fields of measurement of light and color (photometry and colorimetry). In 1931, the CIE established standardized color ordering systems by determining the light source, the observer, and the method for determining color values, regardless of the industry or intended use. The CIE Color Systems utilize coordinates to locate and define color in a color space, (X-Rite, n.d.). The most frequently used systems are: CIELAB and CIELCH.

CIELAB color model

CIEALAB (L*a*b*) is a way of expressing color using Cartesian coordinates to calculate a color in a color space where L* defines lightness, a* denotes the red/green value and b* the yellow/blue value. In Figure 2, the color-plotting system for L*a*b* can be seen. The a* axis runs from left to right (green to red). The b*axis runs from bottom to top (blue to yellow). The L* axis shows the lightness value (X-Rite, n.d.).

CIELCH color model

CIELCH (L*C* h° or L*C*H*) on the other hand uses polar coordinates to calculate a color in a color space. Here, L* defines lightness, C* specifies chroma and h° denotes hue angle, see Figure 2, (X-Rite, n.d.). If desired, H* can be used instead of h°, which denotes a distance rather than an angle.

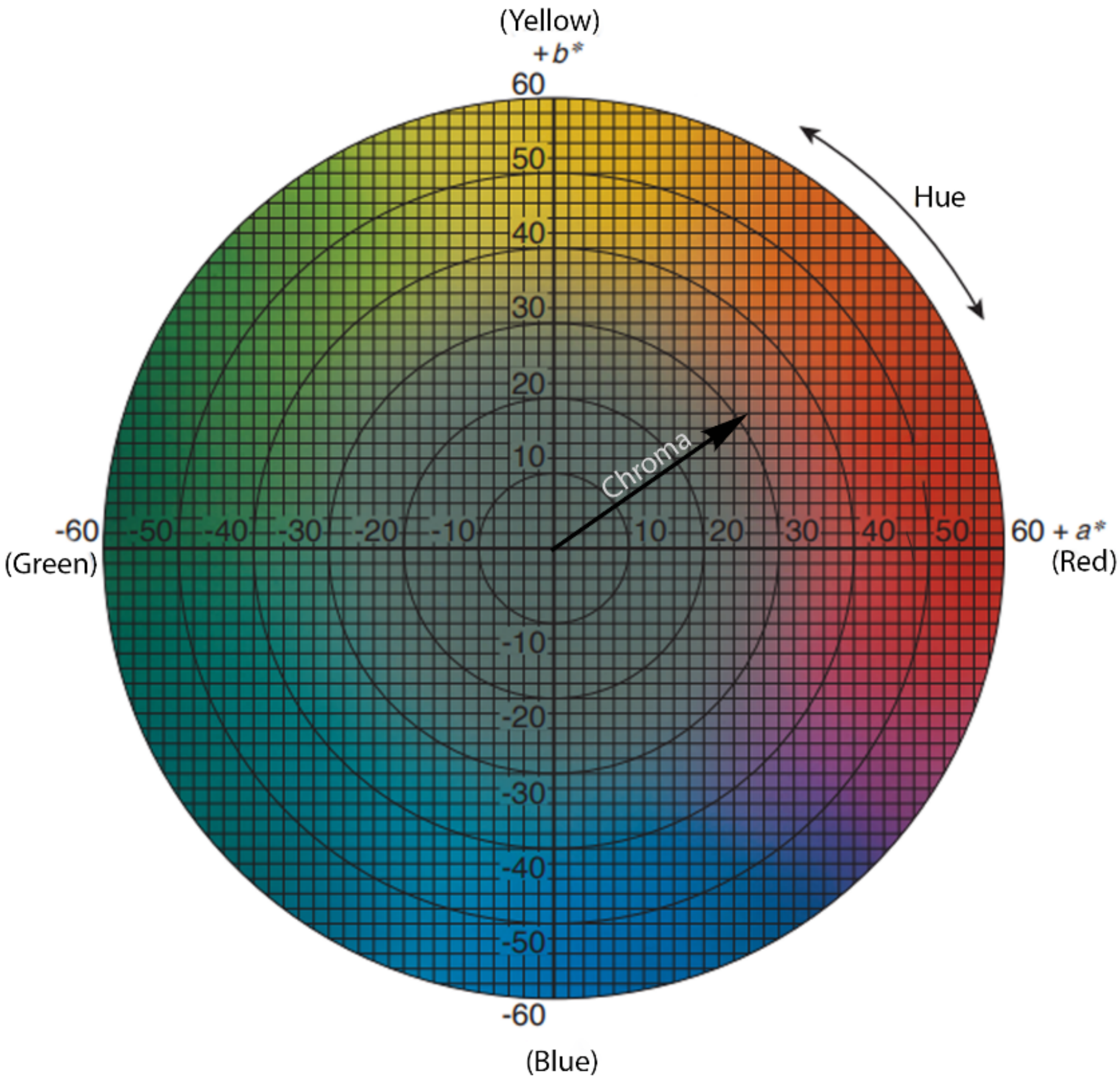


*Figure 2, A color-plotting diagram for L*a*b* and L*C*H. The image shows a cross section of the color sphere, where the L-axis is not visible.*

Color difference models

To assess the measured color difference of two objects using CIELAB and CIELCH, the delta value can be used. The expressions for these color differences are: ΔL* Δa* Δb* (or DL* Da* Db*), and ΔL* ΔC* ΔH* (or DL* DC* DH*). Δ or D symbolizes "delta," which indicates difference.

The CIE color space notations can be described in the following manner (Table 1):

Table 1, CIE color space notations.

ΔL*	+ Sample is **lighter** than reference - Sample is **darker** than reference
Δa*	+ Sample is **more red** than reference - Sample is **more green** than reference
Δb*	+ Sample is **more yellow** than reference - Sample is **more blue** than reference
ΔC*	+ Sample is **more saturated** than reference - Sample is **more dull/grey** than reference
ΔH* Quadrant I	+ Sample is **more yellow** than reference - Sample is **more red** than reference
ΔH* Quadrant II	+ Sample is **more green** than reference - Sample is **more yellow** than reference
ΔH* Quadrant III	+ Sample is **more blue** than reference - Sample is **more green** than reference
ΔH* Quadrant IV	+ Sample is **more red** than reference - Sample is **more green** than reference

Given ΔL* Δa* Δb*, the total difference or distance in the CIELAB system can be stated as a single value, known as ΔE*, Equation 1, (X-Rite, n.d.).

Equation 1, Total difference in ΔE for L*a*b*.*

$$\Delta E^*{}_{ab} = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2}$$

In the same way, ΔE* can be calculated in the CIELCH system given ΔL* ΔC* ΔH* (Equation 2).

Equation 2, Total difference in ΔE for L*C*H*.*

$$\Delta E^*{}_{CH} = \sqrt{(L_2^* - L_1^*)^2 + (C_2^* - C_1^*)^2 + (H_2^* - H_1^*)^2}$$

Human perception of color variation

There is a complex relationship between human perception of color and the wavelengths of light in the visual spectrum. For example, the eye does not detect differences in hue (blue, green, yellow, etc.), chroma and lightness equally. When comparing the three elements, the average observer will most easily see a difference in hue. A difference in chroma is slightly more difficult to notice, and a difference in lightness is the most difficult to notice of the three (X-Rite, n.d.). This relationship of visual acceptability is best represented by an ellipsoid as seen in Figure 3.

Furthermore, the human eye can perceive more variations in warmer colors than cooler ones. In other words, it is easier to tell apart similar shades of orange than it is to tell apart similar shades of blue or green. This is because almost 2/3 of the cones in our eyes process the longer light wavelengths, i.e., reds, oranges, and yellows. (Pantone, n.d.) This phenomenon is represented in Figure 4 where ellipsoids have been mapped on the color space in accordance with the perceived area of acceptance. In the orange area, the ellipsoids are long and narrow, whereas in the green area, they are broader and rounder.

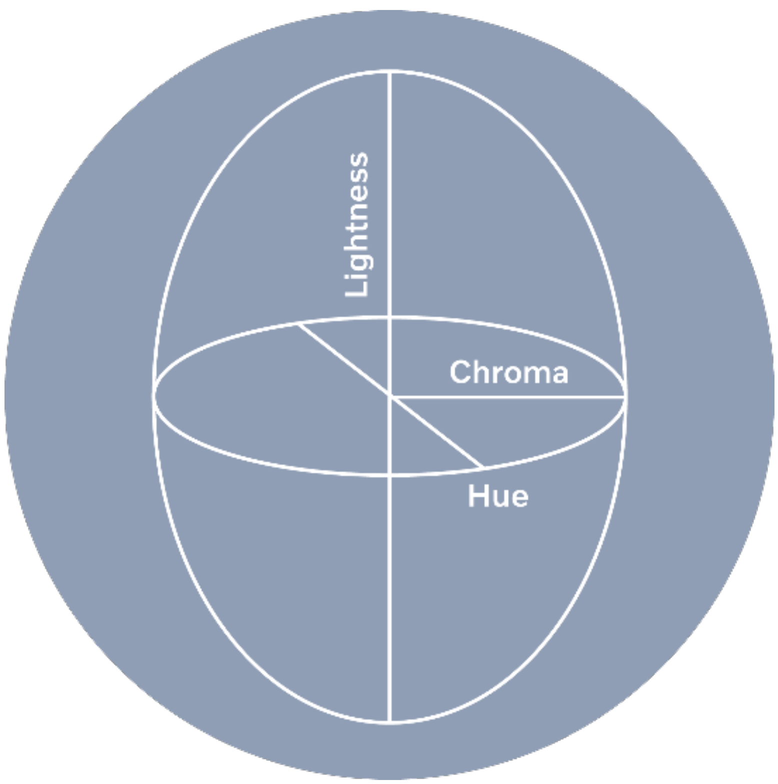


Figure 3, An ellipsoid illustrating the relationship of visual acceptability.

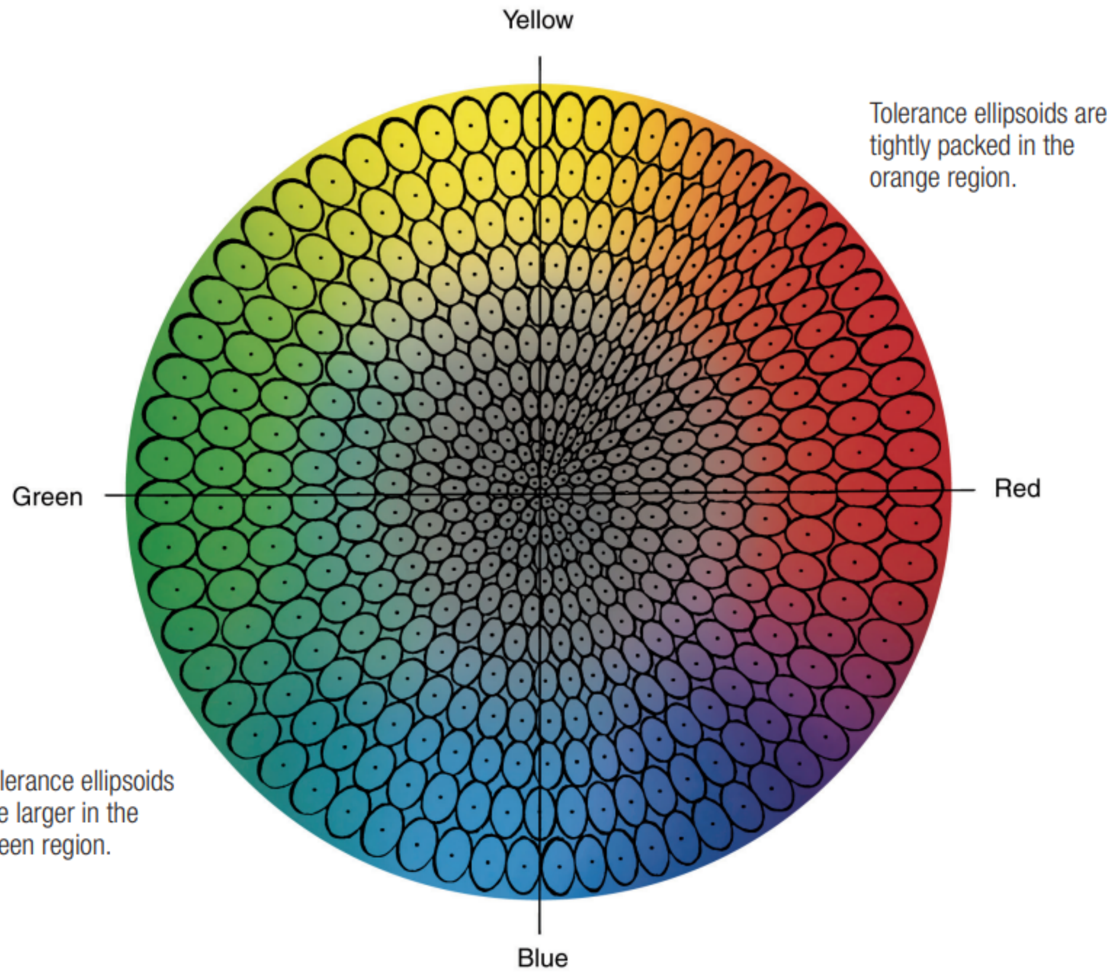


Figure 4, Ellipsoids mapped on the color space in accordance with the perceived area of acceptance., (X-Rite, n.d.)[1]

Material characteristics effect on color

Gloss

The perceived color of an object is affected by the gloss of the surface. Two identical objects with the same true color will be perceived differently (more vivid or dull) depending on the gloss, (Micomlab, n.d.).

Gloss is measured in GU (gloss-units). A high gloss surface, 70 GU or more, with a high specular component will appear as more saturated in color. In other words, more vivid. A semi-glossy surface, typically 20-70 GU, will instead appear less saturated since the specular component is lower due to

[1] X-Rite. (n.d.). A guide to understanding color communication [PDF]. Retrieved from https://www.xrite.com/-/media/xrite/files/whitepaper_pdfs/l10-001_a_guide_to_understanding_color_communication/l10-001_understand_color_en.pdf

the reflected light. Lastly, matt surfaces of 20 GU or less will appear duller due to a low specular component (Micomlab, n.d.).

Texture

According to a study by Wang et al. (2020) pattern scale and shape have a strong influence on the perceived color. The larger the scale of the pattern is the higher the perceived amount of the target color. And the more elongated the pattern shape is the lower the perceived amount of the target color (Wang et al., 2020).

A rough or textured surface will appear more matte than a smooth and even surface, (Benavente et al., 2003). In a study conducted in a previous master thesis it was discovered that rougher surfaces are perceived as less colored than smooth surfaces, (Johansson & Liljenström, 2004).

Color vision testing

To evaluate an individual's color vision ability, a color vision test can be employed. The Farnsworth Munsell 100 Hue Test is widely recognized as an effective means of assessing color vision. This test typically takes approximately 30 minutes to carry out (Farnsworth Munsell 100 Hue Review; X-Rite, n.d.). An expedited version of the Farnsworth Munsell 100 Hue Test, known as the X-Rite Color Challenge and Hue Test, also exists. This test provides a rapid assessment of a person's color vision accuracy (Free Online Color Challenge and Hue Test; X-Rite, n.d.).

Figure 5 depicts the X-Rite Color Challenge and Hue Test. The participant is required to arrange the colored bricks by hue from left to right on each row of the scale. The goal is to create a gradient. The first and last bricks are immovable, while the others can be rearranged. After completing the test, it is scored. A score of 0 indicates no errors and good color vision, while a score of 2 indicates one error, and a score of 4 indicates two errors, and so forth.

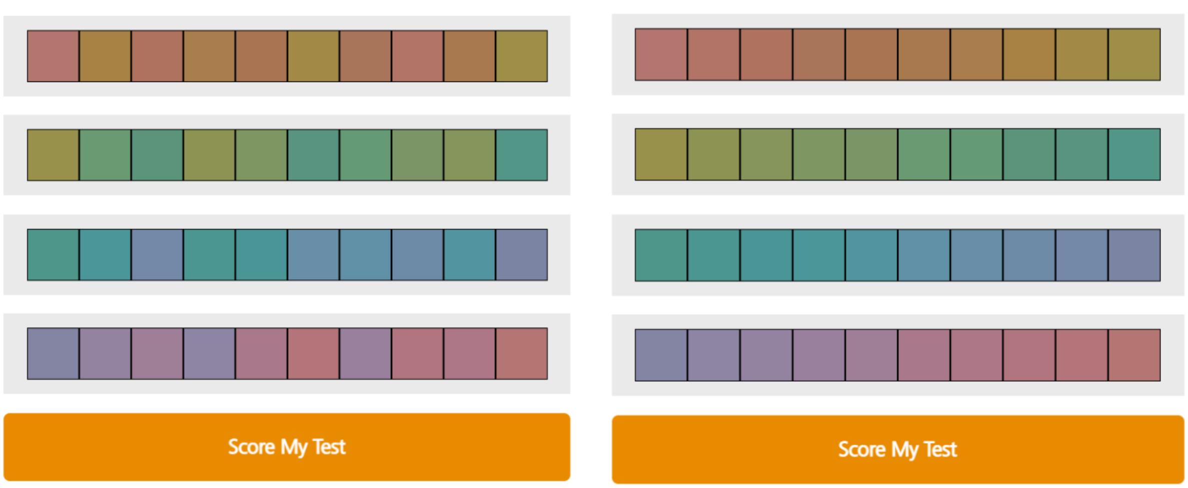


Figure 5, The X-Rite Color Challenge and Hue test. To the left is before the bricks are arranged and to the right is shown when they are arranged correctly.

2.3. Tolerance limits and color tolerances in automotive industry

This section explains how tolerance limits work and their use in the automotive industry.

Tolerance limits

If difference is the number showing how “far apart” two colors are, tolerance is the number that sets the limit for how much of a difference is allowed from a specified color, often called the master or standard. Setting tolerance levels defines what you will accept and what you will reject.

The regions that constitute color tolerances regions within the color space can be shaped differently depending on the tolerancing system. When tolerancing with CIELAB, the limits create a rectangular tolerance box around the standard (X-Rite, n.d.). See Figure 6.

CIELCH tolerancing on the other hand, creates a wedge-shaped box around the standard. Since CIELCH is a polar-coordinate system, the tolerance box can be rotated in orientation to the hue angle (h°), Figure 6 (X-Rite, n.d.). To avoid working with angles, H* can be used instead of h°, which denotes a distance rather than an angle. This creates a rectangular box instead of a wedge-shape, similarly to the CIELAB system.

ΔE00 is a tolerancing system based on ellipsoids. It is considered to provide a better agreement between human visual assessment and measured color difference. The ellipsoids are modeled around the standard color with axis corresponding to hue, chroma and lightness, see Figure 6. The shape and orientation of the ellipsoids in the ΔE00 formula are based on extensive research and experiments to model human color perception and varies in size and shape depending on the position of the color in the color sphere (X-Rite, n.d.).

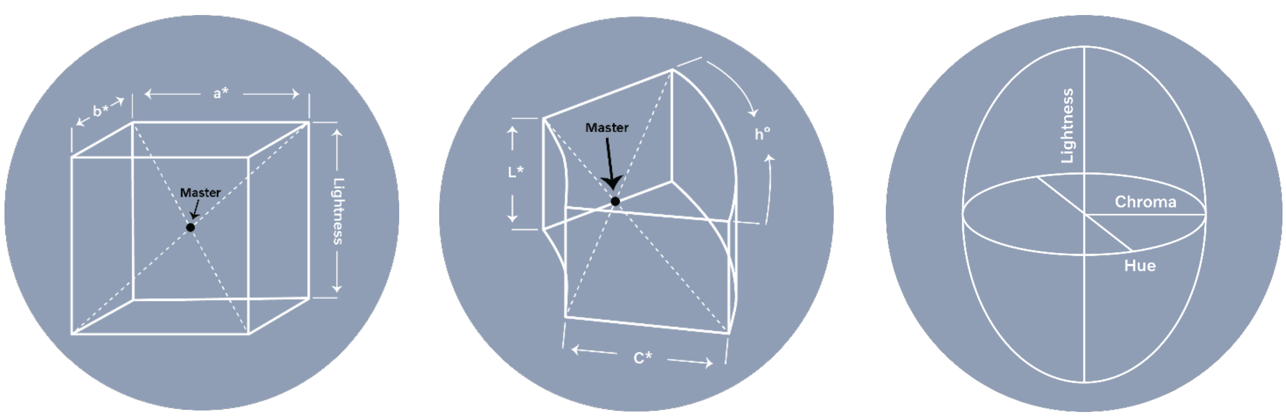


Figure 6, From left to right: CIELAB tolerance box, CIELCH tolerance wedge, ΔE00 tolerance ellipsoid.

Color tolerances in the automotive industry

Within the automotive industry, many different measures are used for expressing color tolerance. This is a direct consequence of the large variety of color difference equations that have been proposed over the years, without one being clearly superior to the others. One of the more popular options is the mathematically simple ΔE which provides the overall difference (E. J. J. Kirchner & J. Ravi, 2012). Another popular tolerance method is to separate the CIELAB or CIELCH values for increased control over each axis. These choices do however bring issues in terms of some visually unacceptable samples being accepted, and visually acceptable samples being rejected. This is a direct result of the rectangular tolerance regions created by the systems. If you want to keep the "bad" colors out, you need to reduce the size of the tolerance region to the point where you inevitably also end up rejecting "good" colors or doing visual overrides of the numerical results. (Balthazar, 2021)

2.4. Standardized light sources and measurement tools

This section describes theory related to standardized light sources and light measurement tools.

Standardized light sources

When assessing samples based on their color, proper lighting is important because the appearance of an object is significantly influenced by the light source it is viewed under. To ensure that all stakeholders in a supply chain evaluates samples under consistent light, industries have developed international standards for the viewing of color. The following three are some examples of them.

D65 – Daylight Illumination (CIE Illuminant D65) is the most commonly used illuminant. This standard illuminant represents a color temperature of 6500K. It is based on actual measurements of the spectral distribution of daylight, (X-Rite, n.d.).

A – Incandescent illumination (CIE Illuminant A). This standard illuminant is yellow-orange in color and has a color temperature of 2856K, (X-Rite, n.d.). It is used for simulation of a warmer light, for example a sunset.

F2 — Fluorescent (CIE Illuminant F2). This standard illuminant has a cool white light and simulates fluorescent lighting commonly used in production and exhibition halls.

Light measurement

A spectrometer is a scientific instrument that is specifically designed to measure the properties of light, including its intensity, wavelength, and spectral distribution. Similar to a camera taking a photograph, a spectrometer captures a snapshot of the light and provides a graph or image of its output. They are commonly used to measure a wide range of wavelengths, from ultraviolet (UV) to visible light (VIS) or near-infrared (NIR), in a single scan, (International Light, 2021).

Light booth

A light booth, also known as a color viewing booth or color matching cabinet, is a specialized device used to evaluate the color accuracy of products and materials under controlled lighting conditions. A light booth typically consists of an enclosed chamber with walls painted in a neutral color, such as gray, to minimize color reflections. The interior of the booth is illuminated with several different light sources, which can be adjusted to mimic various lighting conditions, such as daylight or artificial lighting.

The purpose of a light booth is to provide a standardized environment for visual color assessment, enabling accurate color comparisons between different samples. For instance, manufacturers may use a light booth to check whether their products match a specific color standard or to detect any color variations between batches of materials.

2.5. Color master plaque and visual assessment

This section provides theory regarding color plaques and the visual assessment of them.

Color master plaque

A color master plaque, also known as a color reference chart, is a standard tool used in color management to establish comparisons of color, texture, and gloss that are consistent with the designer's intent. The master plaque serves as a reference point for assessing whether the colored components match the desired color, gloss, and texture standards. This tool is applied in various industries, including the automotive sector. The master plaque typically comprises different textures, allowing for the comparison of multiple textures against the same standard. A visual representation of a master plaque is provided in Figure 7.

Figure 7, A master plaque with 3 different textured areas.

Visual assessment of color plaques

The visible color difference between two plaques can be assessed by placing them next to each other. During the comparison process, a trained inspector will visually compare the color and gloss levels of the plaques under the standardized lighting conditions and assess any differences between the color of the plaque and the reference standard. It is more difficult to compare the colors to each other when the plaques are well apart because peripheral color vision is inevitably implicated, (Laborie et al., 2010).

2.6. User studies

User studies are an essential part of the design process for any product or service. These studies involve collecting feedback and data from users to understand how they interact with a product or service and identify areas for improvement. User studies can take many forms, from surveys and focus groups to usability testing and user interviews and can collect both quantitative and qualitative data depending on chosen method, (Ri.se, n.d.).

When conducting user studies, it is important to consider the goals of the study and the audience being studied. The goals of the study will guide the types of questions asked and the methods used to collect data.

In conclusion, user studies represent a valuable method for gaining insight into users' perspectives and attitudes towards a product or service. Furthermore, user studies are an effective method to use when seeking to gauge customers' acceptance levels of color tolerances, as they allow for the collection of targeted and nuanced feedback.

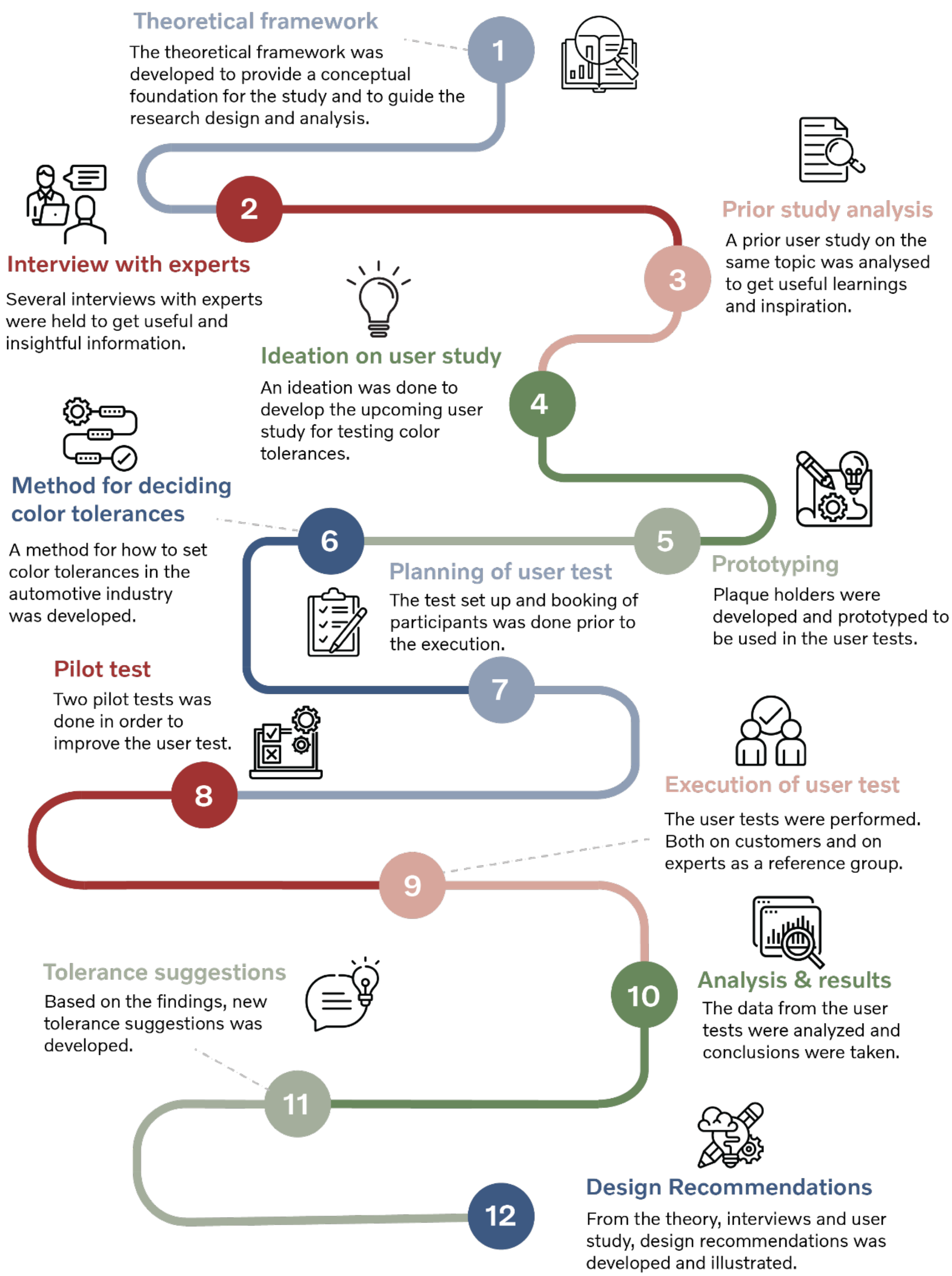
3

EXECUTION

The present chapter focuses on the execution of the research project. This chapter details the specific steps taken to carry out the user study, including the design of the study and procedures for analysis. The chapter also provides an overview of the participants involved in the study and the test setup. Through a thorough description of the procedure of the user tests, this chapter aims to provide readers with a clear understanding of how the study was conducted and to demonstrate the integrity and rigor of the research. This chapter also presents the sources of errors and the process of developing design recommendations.

3.1. Process map

Below is a process map that illustrates the different steps taken during the execution phase.



3.2. Preparation and planning of user tests

This section provides a comprehensive account of the preparation and planning of the user tests including the selected colors, the plaques, ideation, prototyping and development of method for measuring color tolerances.

Selected colors for study

In this study, two colors used in the interior of VCC cars have been investigated. One of them is a light beige color by the name of "Dawn" and the other is a dark grey, almost black color, by the name of "Charcoal Solid". These specific colors were selected for the investigation due to their high frequency of use in the company's cars. This strategic selection aimed to ensure the study's relevance to the majority of the company's customer base and to gain valuable insights into their preferences regarding the most frequently utilized colors.

Figure 8, Dawn plaque to the left and Charcoal Solid plaque to the right.

As seen on the image above, the plaques are divided in sections with varying degrees of texture and gloss. In this study, only the section containing the fine grain surface has been investigated which is the top section seen on Figures 8. This was decided as the fine grain texture is used as a basis for all color developments of other materials/appearances in the car specifically for these two colors. In other words, it is the "master of masters".

Plaques

To investigate how requirements regarding color tolerances can be modeled so that they correspond to the customers' expectations, plaques with slight variations to the two masters, Dawn and Charcoal Solid, were necessary for the purpose of the user studies. The plaques utilized in the study were procured and fabricated by a specific supplier selected by VCC. These plaques were meticulously produced to possess certain variations in lightness, hue, and chroma relative to the two master plaques. As seen in Figures 9 and 10, each plaque has been labeled with a letter for ease of identification. An extra master plaque was also produced for both colors as can be seen in Figure 9 and 10. The purpose of this is described in a later chapter.

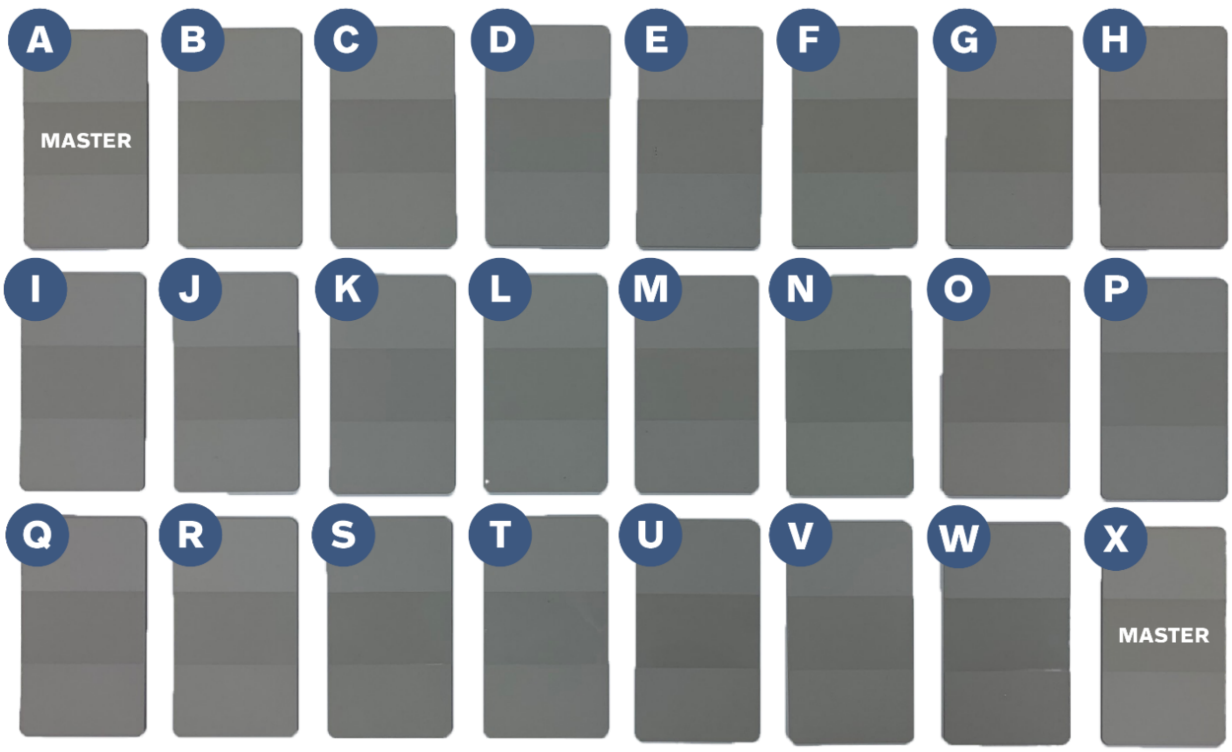


Figure 9, Dawn plaques used in the study.

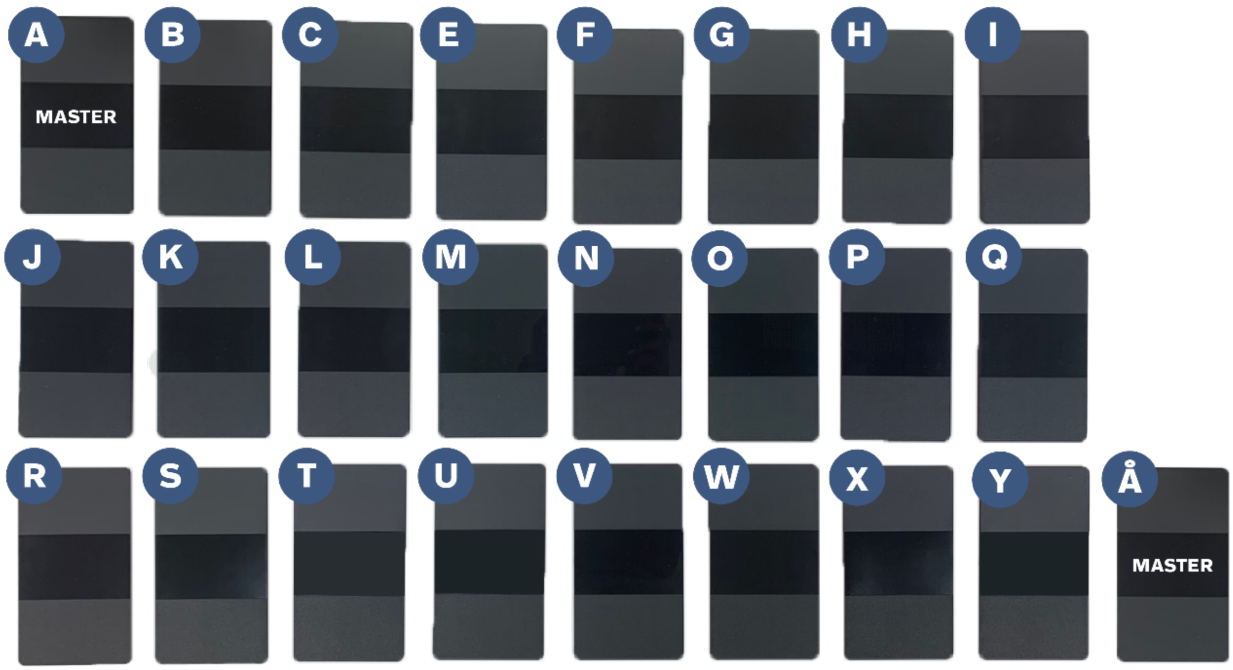


Figure 10, Charcoal Solid plaques used in the study.

The aim was to attain plaques with the exact variances specified in the columns on left side in Appendix 1 and Appendix 2. To ensure the desired color properties, all plaques were measured with a spectrophotometer when delivered from the supplier. The spectrophotometer measured both L*C*H* and L*a*b* values, with both SCI and SCE modes. The decision was made to use the L*C*H* system for Dawn since it is a color located far away from the center of the color sphere. In other words, a change in hue would result in a far more significant visual difference than if it had been located close to the center where colors are less vibrant. As for Charcoal Solid, the L*a*b* system was chosen because of the color's position close to the center of the color sphere.

The spectroscopic analysis revealed that most of the plaques differed slightly from the desired color properties, and consequently, the measured values were adopted for use in the study. Furthermore, it was determined that the SCI values exhibited no significant differences relative to the SCE values, and as a result, the study focused exclusively on the SCI values. The gloss was also measured on the plaques. However, the gloss values exhibited only minor discrepancies and were deemed acceptable from a tolerance standpoint.

As mentioned previously, each plaque was labeled with an alphanumeric code for efficient sorting and organization. The plaques, along with their corresponding color values, can be found in Appendix 1 and Appendix 2. Notably, some of the measured values exhibited marked differences from the desired values. The measured values are the ones used in the study. With regards to the Charcoal Solid plaques, plaques D and Z were excluded from testing due to the fact that plaque D differed substantially from the desired values, while plaque Z was never intended to be used in the study from the beginning.

Prior pilot study

A prior pilot study was conducted in 2022 to assess interior color tolerance levels. The study involved 12 participants from the attribute department Perceived Quality at Volvo Cars, with 25% of them being color experts. Each participant compared 9 plaques of different variations against a master plaque. As well as the master plaque compared with another master plaque.

All comparisons were done in a light booth. Participants were asked to determine whether they perceived a difference between the plaques, explain any observed differences, and judge whether the match was acceptable. Responses were analyzed and plotted on a graph to determine the acceptable limits.

The pilot study was solely conducted to gain knowledge in preparation for the project described in this report.

Ideation of user study

One of the objectives of the study was to investigate customers' perceptions of interior color tolerances in cars. An ideation phase was conducted to design the study, taking into account certain limitations. The study needed to be conducted under uniform conditions for all participants, as color perception varies under different conditions. Therefore, the study was restricted to be performed in a certified light booth. It was also of importance to use the specific light booth currently utilized for color assessment by PQ at VCC. The reason for this was to ensure the exact same conditions for the participants of the user study as for the color experts at VCC. Because of this, the location of the study was limited to the VCC office in Gothenburg.

Before the study, the plaques with color variations compared to a master plaque was provided by VCC. These plaques were chosen to be used in the study to determine customers' perceptions of the color differences. The design of the test was inspired by the prior pilot study conducted in 2022, which also aimed to investigate customers' color tolerance levels of interior car components. It was determined that the best approach was to examine the plaques in a light booth, one by one, compared to the master plaque. However, concerns were raised that the light booth lacked a sense of reality since a real car interior context was missing. Therefore, it was decided that a real car should be used in the test as well, to provide the participants with this context and help them understand the true environment of the color judgement.

The use of a real car in the test provided a chance to make comparisons between the responses given in two different environments: the light booth and the car. In other words, the car could be used to not only help uses understand the context, but also to assess some of the plaques. Analysis of the test results could possibly show if the responses for the light booth differed significantly from the responses given in the car. Possibly showing if participant were more critical in one of the contexts.

A frame that could hold the plaques in the car was developed and tested, and a scenario was created to provide context to the participants. The proposed methodology was to allow participants to inspect three of the plaques in three different positions in the car, each compared with a master plaque, to provide context and familiarity. Following this, participants would examine all the plaques in a light booth, as done in the prior study.

Prototyping

Three sets of plaques were intended to be positioned adjacently in a vehicle and judged during the user tests. To achieve this, a specific holder for the plaques was designed. The plaques were precisely measured, and a preliminary design of the holder was produced using computer-aided design (CAD). A primary version of the holder was fabricated using 3D printing technology and underwent examination of durability, size, and geometry. Subsequently, certain measurements were adjusted for further refinement, and three definitive plaque holders were manufactured. The lower portion of the holders was created using 3D printing technology, while the upper section was crafted using sheet metal, coated with a neutral grey color, S 3000-N, and then assembled using double-sided tape. The plaque holder can be seen in Figure 11.

Figure 11, A plaque holder. On the right with two Charcoal Solid plaques inserted.

Subsequently, the three plaque holders were affixed to the vehicle in three distinct locations during the examinations, as illustrated in Figure 12. The positions were selected based on their different lighting conditions and viewing angles. These placements were discussed and selected with help of color experts at VCC. Furthermore, these locations were chosen to ensure the capture of distinct angles and lighting conditions that are present within the vehicle.

Figure 12, The 3 final plaque holders placed on their correct positions in the car. Described more in detail in the text above.

Development of method for measuring color tolerances

The primary objective of the method for measuring interior color tolerances is to ensure that the overall color of a product aligns with customer expectations. An approach to achieve this goal is by establishing tolerance levels based on customer acceptance rates. In this regard, a method was proposed that considers customer acceptance rates of 80%, 85%, and 90% as tolerance levels, taking into account the brand's premium qualities and emphasis on high customer satisfaction. It was essential to keep the tolerances simple and sufficient for automotive companies to implement. Hence, the new tolerance levels needed to be rectangular and have a fixed value in each direction (L*a*b or L*C*H), as implementing the ΔE00 tolerance would be complex and not indicating which direction the deviation is. Additionally, for ease of use, the tolerance levels needed to be whole or half numbers ranging from 0.1 to 0.15 to 0.2 and beyond.

Once the user study is completed, the plaques can be illustrated on a scatter chart and marked as approved or not approved, based on the chosen tolerance levels. A rectangular box can then be adjusted to fit the area where the limits go between the plaques rated as approved and not approved, as illustrated in Figure 13, from which the tolerance levels can be read. It is important to note that customer opinions on color vary depending on the color, and the new tolerances is expected to only apply to the examined colors in this study, Dawn and Charcoal Solid.

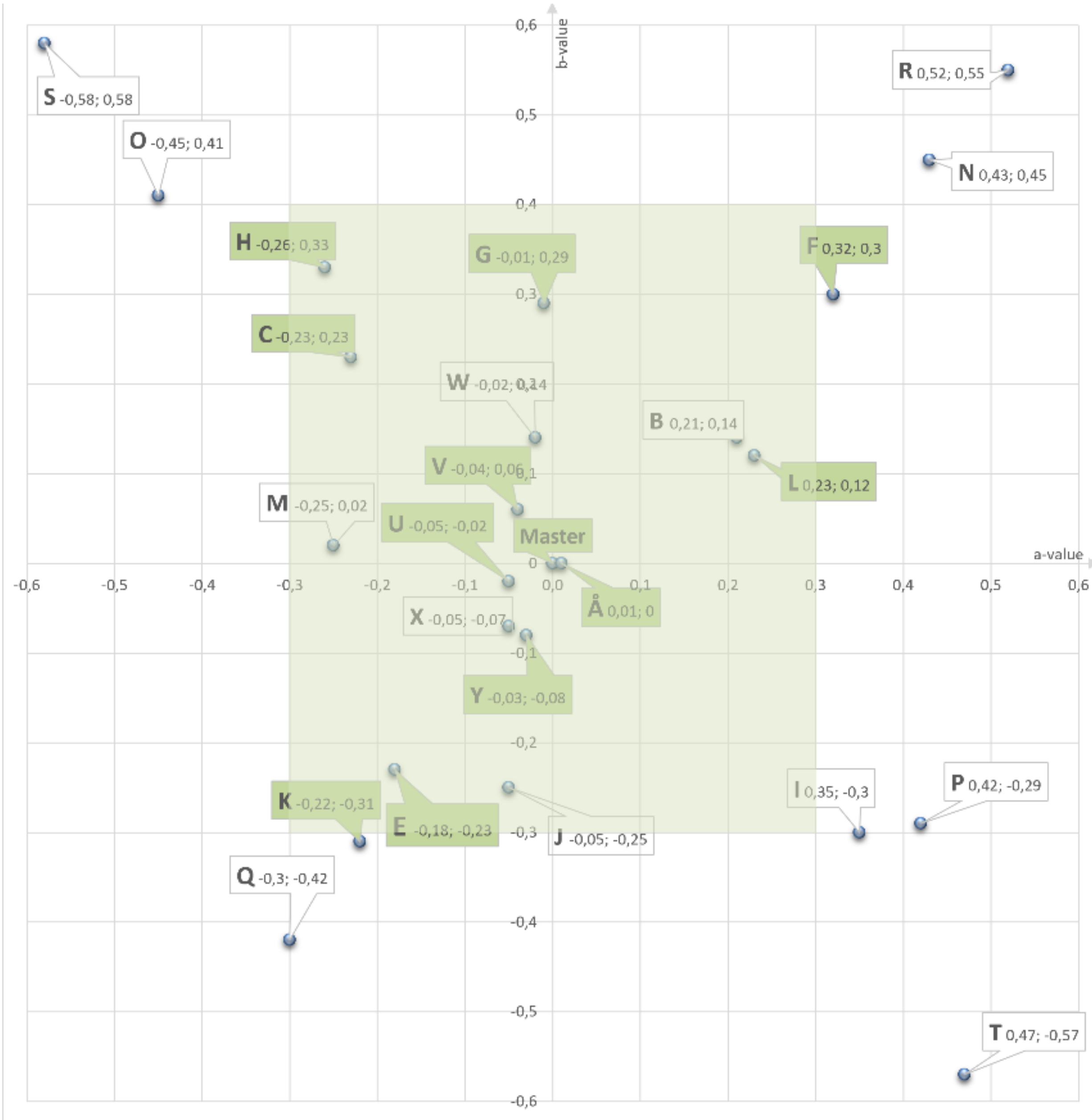


Figure 13, A scatter chart where the approved colors are marked in green. A tolerance limit- rectangle have been adjusted according to the approved colors and is shown in green.

3.3. Execution and implementation of user test

This section explains how the user tests were designed and executed, including relevant tools, information about the participants, and the overall test layout.

Light booth used in study

The light booth used in this study is called a SpectraLight QC which is a light booth used for the most critical visual assessments, Figure 14. It has 7 light sources including dimmable filtered-tungsten halogen daylight (class A) and provides the most accurate daylight simulation available for optimum visual assessment, (*Light Booths, X-Rite*, n.d.).

Figure 14, The light booth used in this study.

To assure the adequacy of the lighting conditions within the light booth, a spectrometer was employed to measure the light spectrum. Figure 15 depicts the color spectrum of the light conditions during D65 within the light booth, while Figure 16 illustrates the spectrum for standardized CIE D65 light which is currently the best representation available of simulated natural daylight. A comparative analysis of the two spectra reveals that the spectral distribution is similar.

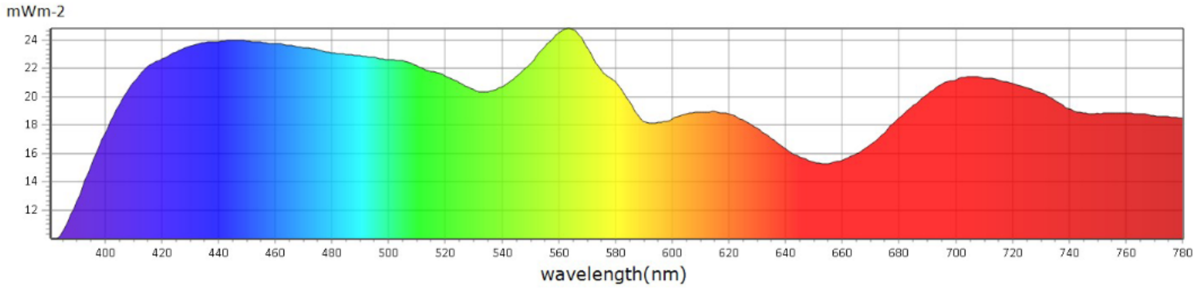


Figure 15, D65 color spectrum in light booth.

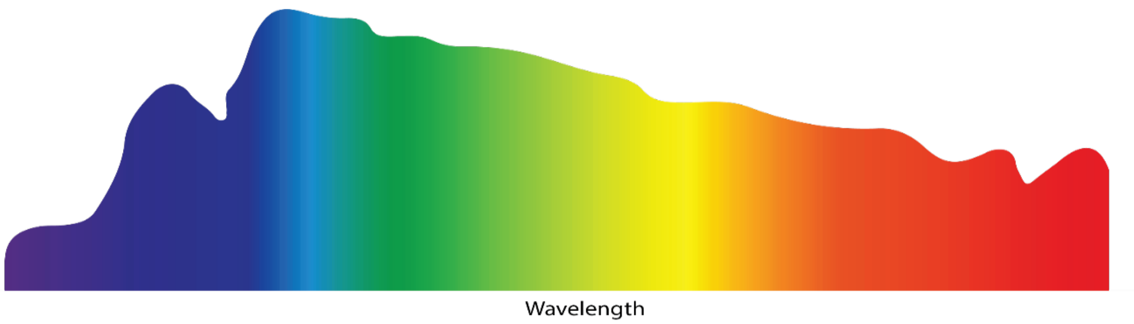


Figure 16, Standardized CIE D65 light.

Cars used in the study

In the first part of the test, the participants were to be seated in a car with an interior corresponding to the color they would be judging, i.e., a light beige interior for Dawn and a dark grey/black interior for Charcoal Solid. This was decided in order to help participants visualize the true context of the color judgment. To achieve this, two different cars had to be incorporated in the tests, one with light interior and one with dark interior. Since it was imperative to conduct the user tests of Dawn and Charcoal Solid in an identical manner, the cars were selected to be of the same model, Volvo XC60. See Figure 17.

Figure 17, XC60 with light interior to the left, and dark interior to the right.

Color vision test

To ensure that participants had adequate color vision, an online color vision test created by X-rite was conducted at the beginning of each user test. The computer screen used for this online test was color-calibrated using a Spyder X PRO monitor calibration device, with the overhead lights in the test scene turned off to ensure correct color rendering. Participants who scored 4 or higher on the test, corresponding to 2 or more faults, had their results individually examined afterwards to determine the accuracy of their answers. Participants who provided off-target responses were excluded from the test results and analysis.

Participants of the user tests

The user studies were conducted exclusively at the VCC office with employees located at the site as participants. None of the participants worked in a field related to color tolerances, except for the reference group. Invitations to partake in the user studies were extended via email, wherein a short explanation of the study was provided alongside an invitation to take part. The information was carefully selected as to not provide participants with too much knowledge on the study's aim, which could cause unintentional bias.

For each of the two colors, 35 people participated in the user tests. Of these, 5 people were color experts from PQ, and formed the reference group. In other words, a total of 70 people took part in the tests.

Information regarding the participants can be seen in Table 2 below.

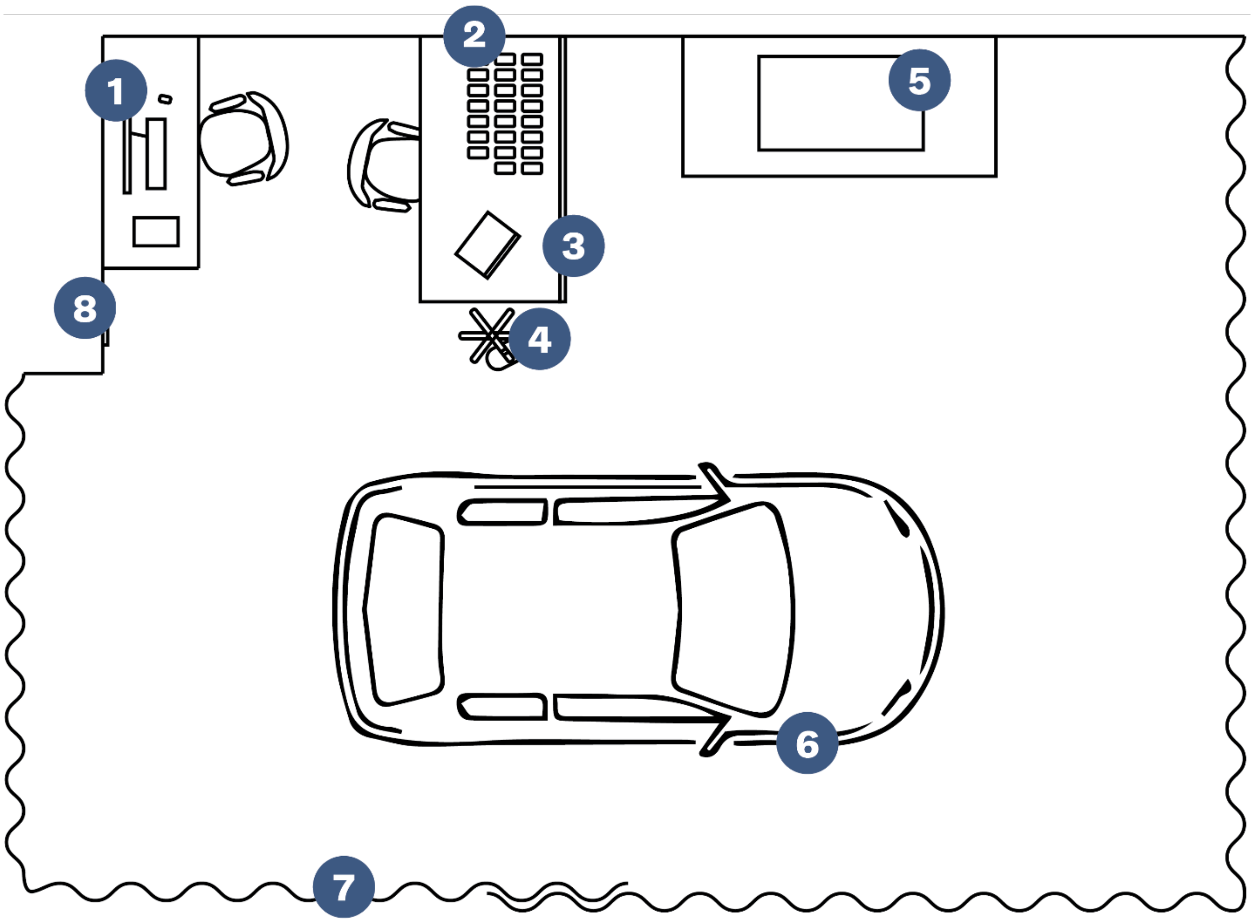
Table 2, Information regarding the participants of the user studies.

	Dawn	**Charcoal Solid**
Number of participants	30 customers, 5 experts	30 customers, 5 experts
Age range	23-58 years old	19-58 years old
Gender	37% women, 63% men	63% women, 37% men
Car ownership	70% have a car	37% have a car

Test setup

Due to the requirement of controlled lighting conditions and the need of shielding from external lighting, the LUX Center at VCC Gothenburg was chosen as the location for the user study. This specific area is outfitted with a blackout curtain and adjustable, controlled overhead lighting to facilitate the experimental setup, which consisted of the vehicle, light booth, calibrated screen, and a shielded table for the plaques, see Figures 18 and 19.

Figure 18, The setup in LUX with the car and the light booth in the background.



1. Calibrated screen for color test
2. Plaques
3. Screen for hiding view of plaques
4. Coat rack with white coat for participant
5. Light booth
6. Volvo XC60
7. Blackout curtains
8. Control pad for overhead lights

Figure 19, Overview of the setup

In the first part of the test, the lights were switched off in the area to facilitate accurate color rendering on the calibrated screen employed for the color vision test. During the second part of the test, the lighting conditions were adjusted to simulate daylight, with a lux level of 6500 K. Finally, in the third part of the test, the overhead lights were once again switched off, while the light booth was illuminated using D65 lighting.

In the light booth, the plaques were placed on a 45° angled frame, about 20 cm from the front edge of the booth, allowing each participant to view the plaques from approximately the same angle and distance, Figure 20. Each comparison was made in a pairwise manner, always displaying one master plaque either on the left side or the right side. Once the plaques were positioned on the angled frame, a thin sheet of metal in a neutral grey color with a small “window” was placed on top of the plaques in order to isolate the area with the fine grain texture. The metal frame covering the plaques also helped remove any visual distractions from the color assessment.

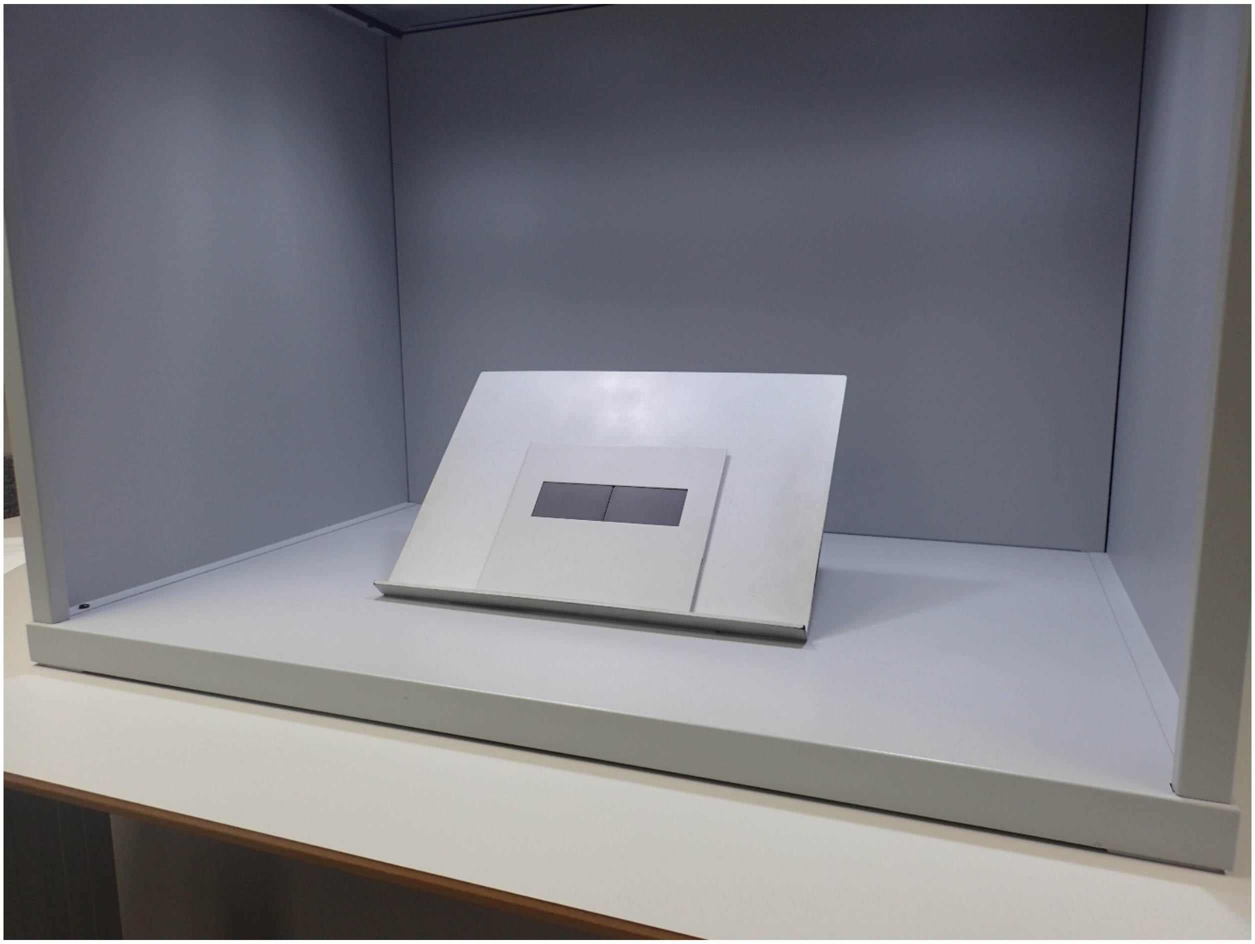


Figure 20, 2 plaques placed in the plaque holder on the stand.

To keep participants from seeing the order of the plaques in the comparisons, they remained hidden from view behind a screen, see Figure 21. The switch of plaques between each comparison was also done behind the screen. This way, participants would not be able to tell which plaques were selected each time, or that one plaque always remained the same, meaning the master plaque.

Figure 21, Test setup with screen to hide view of plaques from participants. The light booth can be seen in the background.

Plaque comparison

To investigate customers' perceptions of color tolerances, the study was designed in a way that would allow test participants to judge the selected color variations in a pairwise comparison of two plaques. As the master plaque holds the intended appearance, it is reasonable to assume that the level of acceptance for any deviations is best investigated by a comparison of the master plaque and the deviated plaque. Thus, the decision was made to have the master plaque present in every comparison for all test participants. This can be seen in Table 3, where the test order on Dawn for participant 1 and 2 is shown. In the "Surface ID" column, the order in which the plaques are presented to the test participant is decided. In the "Order" column, the placement of the master is decided. The master is labeled A, and other all letters correspond to the deviated plaques.

Table 3, An illustration of how the plaques were sorted and shown for the test organizer during the user tests. The order for participant 1 is shown to the left and the order for participant 2 is shown to the right. Both people tested the Dawn plaques.

Respondent ID	Surface ID	Order
1	B	AB
1	M	AM
1	S	AS
1	C	AC
1	P	PA
1	F	AF
1	O	OA
1	I	IA
1	R	RA
1	T	TA
1	E	AE
1	H	AH
1	V	VA
1	N	NA
1	D	DA
1	Q	AQ
1	X	AX
1	U	AU
1	J	JA
1	L	LA
1	W	AW
1	K	AK
1	G	GA

Respondent ID	Surface ID	Order
2	F	FA
2	T	TA
2	Q	AQ
2	K	AK
2	J	JA
2	O	AO
2	E	EA
2	I	AI
2	D	AD
2	G	AG
2	U	UA
2	S	AS
2	P	PA
2	W	AW
2	N	NA
2	M	AM
2	X	AX
2	L	AL
2	V	VA
2	R	AR
2	B	BA
2	H	AH
2	C	AC

As can be seen in Table 3, a comparison between the two master plaques was also included in the test. For Dawn, the master plaques are A and X, and for Charcoal Solid the master plaques are A and Å. This was decided in order to see how many of the participants would claim that they could see a difference between two practically identical colors. This would verify if participants were truthful in their answers and did not give random responses in their tests.

To prevent participants from experiencing "order effects" in the user tests, plaques were assigned in a randomized order. This was particularly important in avoiding two main types of order effects that can occur in user testing: fatigue and practice effects.

The fatigue effect can occur when participants become increasingly tired or bored as the test progresses, in this case from viewing and evaluating a certain number of plaques. This can lead to a decrease in performance and accuracy and can skew the results of the study if the order of the plaques is consistent across all participants. By randomizing the order of plaques, it minimizes the impact of fatigue effects. Practice effects, on the other hand, can occur when participants become more familiar with the testing environment and procedures as the study progresses. This can lead to an increase in performance and accuracy as participants become more skilled at evaluating the plaques. By randomizing the order of plaques, it can also minimize the impact of practice effects by ensuring that the same plaques are not always viewed in the same order, and that each participant has an equal chance of encountering each plaque at any point during the test.

The position of the master plaque (left or right) in each comparison was also randomized to prevent participants from realizing that it was always present in the test. If the master plaque had been positioned at, for example the left side during the entire test, participants may have sensed that the left plaque was always the same. Subconsciously or not.

Overall, randomizing the order of plaques between participants, and the placement of the master, was an important step in the user testing to ensure that the results are reliable, valid, and generalizable.

Pilot tests for improvement

Two pilot tests were conducted prior to the main study to improve the testing procedures and identify any flaws. The first pilot assessed the equipment's suitability and practiced the testing, while the second pilot tested the complete protocol to identify any weaknesses. These pilots allowed for a more accurate, efficient, and confident final study.

Procedure of the user tests

The study involved testing the colors Dawn and Charcoal Solid separately with different participants to ensure accuracy and efficiency. Additionally, a reference group consisting of color experts from PQ was employed to conduct the test. The whole test procedure can be seen in detail in Appendix 3.

The study was conducted in three parts. In part one, participants signed a GDPR document and answered a set of questions about their age, gender, profession, car ownership, and vision impairments. Afterwards, they conducted the digital X-Rite color vision test. When finished, the results were written down.

In part two, participants sat in the front seat of the car, with a test organizer behind them in the backseat. The overhead lightning outside of the car was set to imitate daylight. In the car, they were given demonstrations of how components could be situated that were supposed to "match" color wise. The participants were then given a scenario and asked to evaluate the color of interior components using two plaques placed in the three different positions in the car. Participants were required to answer yes or no to whether they saw a difference between the plaques, explain the difference if they saw one, and judge whether the match was acceptable or not.

In part three, participants stood in front of a light booth with white coat that would minimize reflections from their own clothes and evaluated the same type of plaques as before. The overhead lights of the scene were turned off and the light booth was set to D65 (simulated daylight). The table with the light booth was adjusted to be in elbow height of the participant. The participant was then asked to look into the light booth for about 1 minute in order for their eyes to adjust to the lightning conditions while a continuation of the instructions was given.

The plaques were then placed on the 45° angled frame and presented to the participant in a specific order. For each comparison, participants were asked the same questions as in part two; "*Do you see a difference between the plaques?*" If yes, *"Can you describe the difference?"* And lastly, "*Do you think that this match is acceptable?".* Participants were only allowed to look at each comparison for about 10 seconds. This was decided in order to avoid eye fatigue based on advice given by an expert in Visual Ergonomics.

The study was conducted with the goal of understanding how customers perceive the color of interior components in a car. Participants were reminded that there were no right or wrong answers and were encouraged to provide their honest opinions.

3.4. Development of design recommendations

To initiate the process of developing design recommendations aimed at creating more forgiving appearances regarding color variation in the automotive industry, a comprehensive review of the current body of literature and theoretical studies on color perception and tolerance was conducted. This allowed for a foundational understanding of the current state of knowledge in the field, as well as identifying areas for further research.

Subsequently, interviews were conducted with automotive designers and color experts to gain insights into the existing color tolerance requirements and limitations in the industry. The outcomes of these interviews provided a deeper understanding of the common challenges and constraints encountered in meeting existing color tolerance requirements, along with opportunities for improvement.

Furthermore, valuable insights were obtained from user tests conducted to measure color tolerances. These data served as critical information for developing the design recommendations.

After collecting and analyzing data from these sources, design recommendations was developed to improve color tolerance appearance in the automotive industry.

4

RESULT & ANALYSIS

The present chapter is dedicated to the results and analysis of the research project. This chapter provides a comprehensive account of the data collected during the study and presents the findings of the study. The chapter also delves into the analysis of the results, with a focus on identifying patterns, themes, and relationships within the data. Through an in-depth examination of the results, this chapter seeks to answer the research questions. By presenting the findings in a systematic and structured way, this chapter aims to provide readers with a clear understanding of the implications and significance of the research project.

4.1. Summary of the data from the user tests

An analysis was conducted to summarize the responses to the following inquiries in the user tests regarding the assessments of plaques: "*Do you see a difference between the plaques?" and "Do you think that this match is acceptable?".* The findings are visually presented through bar charts, which can be viewed in Figures 22 and 23 for Dawn plaques, as well as Figure 24 and 25 for Charcoal Solid plaques. Each letter in the bar charts correspond to a specific plaque.

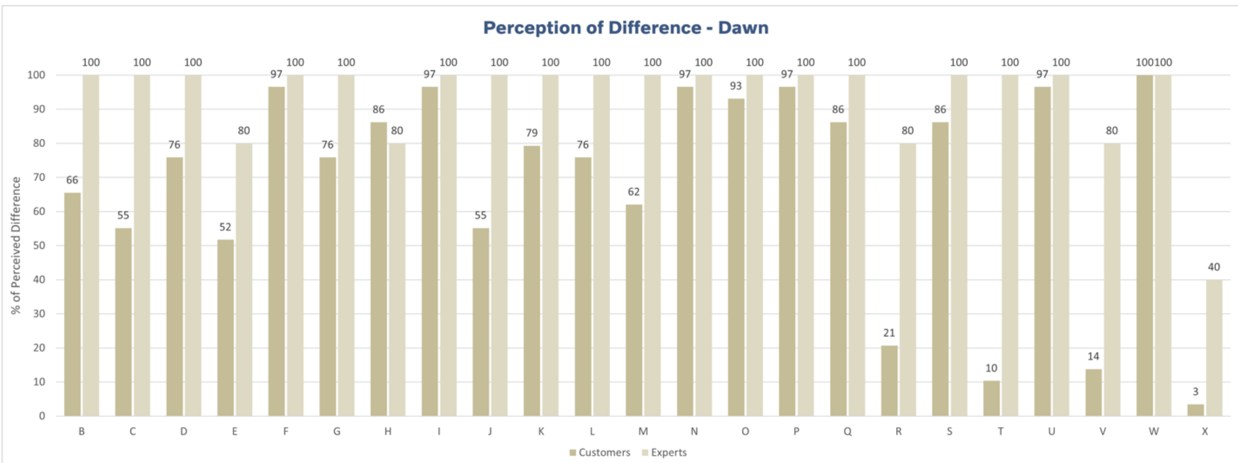


Figure 22, Bar chart showing the percentage of customers and experts who see a difference between the Dawn plaques and the master. The letters correspond to the different plaques.

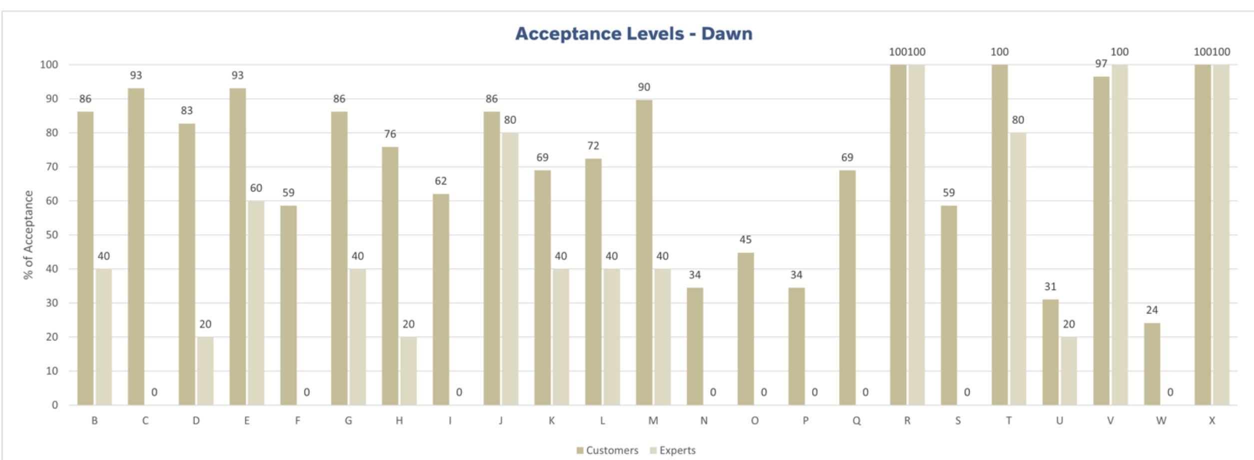


Figure 23, Bar chart showing the percentage of customers' acceptance rate on the Dawn plaques compared to the master. The letters correspond to the different plaques.

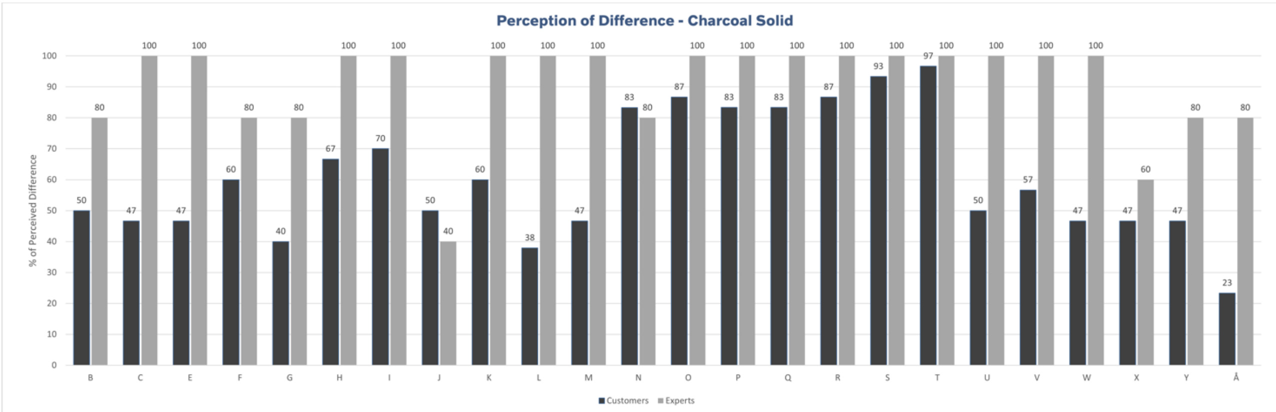


Figure 24, Bar chart showing the percentage of customers who see a difference between the Charcoal Solid plaques and the master. The letters correspond to the different plaques.

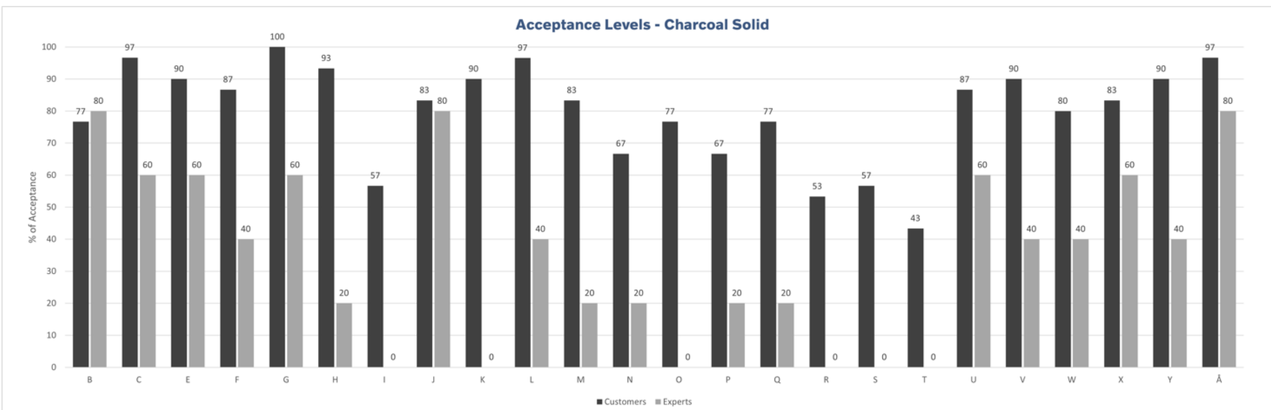


Figure 25, Bar chart showing the percentage of customers' acceptance rate on the Charcoal Solid plaques compared to the master. The letters correspond to the different plaques.

As depicted in Figures 22 and 24, it can be observed that customers, in general, perceive less differences between the plaques compared to the experts. Moreover, customers exhibit a greater degree of acceptance towards the combinations as opposed to the experts, see Figure 23 and 25. Thus, it can be concluded that customers are more tolerant towards color variations than the experts. Notably, the experts identify a considerably higher number of disparities between the plaques compared to the customers. When assessing a master plaque against another master plaque, merely 3% and 23% of customers reported any discernible differences, whereas 40% and 80% of the experts did so (see plaque X in Figure 22, and plaque Å in figure 24). One possible explanation for this could be the experts' heightened focus on identifying disparities.

Figures 26 and 27 demonstrate the correlation between customers' perceived differences and satisfaction rates for Dawn and Charcoal Solid, respectively. The results indicate that a high percentage value of perceived differences is associated with a lower acceptance rate, and conversely, a low percentage value of perceived differences is linked with a higher acceptance rate.

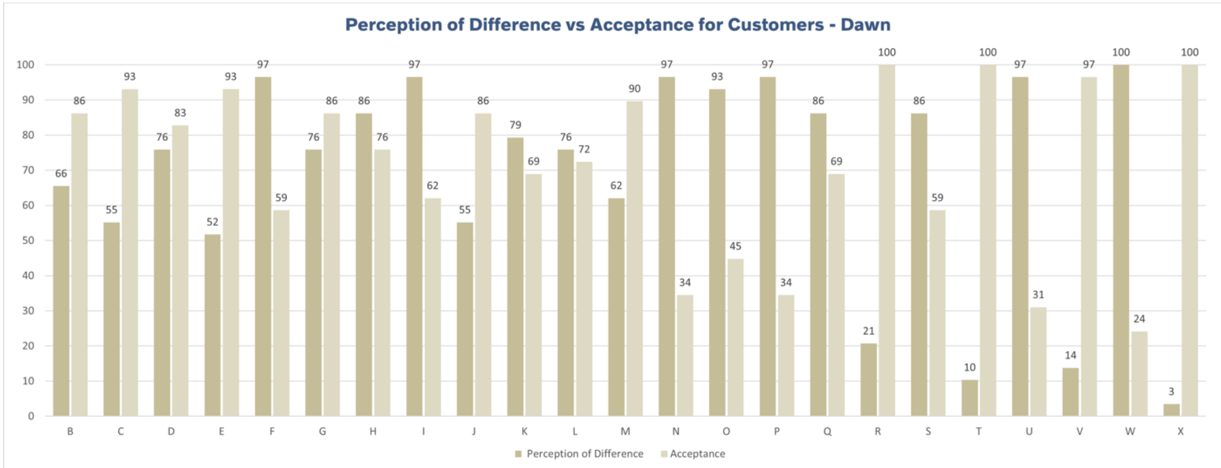


Figure 26, Customers perception of differences compared to their acceptance rates for Dawn, shown in percentages. The letters correspond to the different plaques.

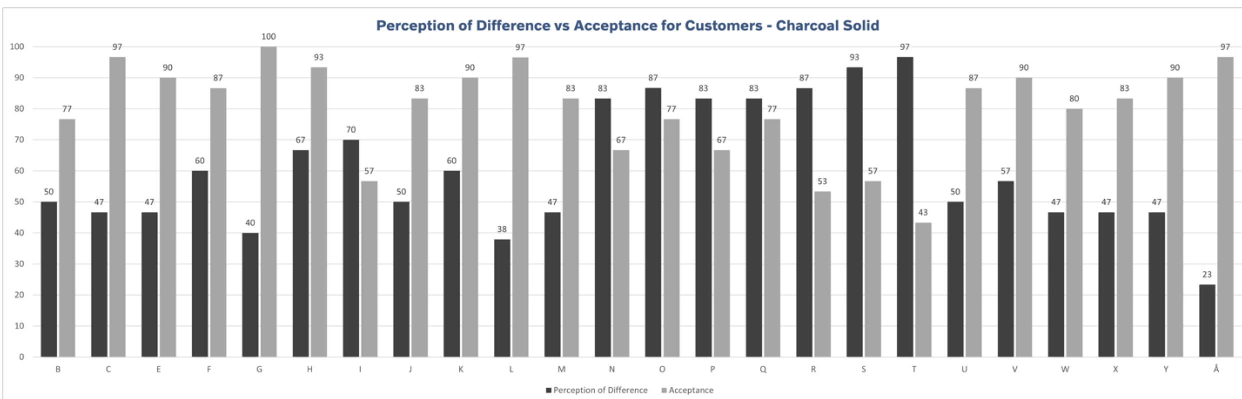


Figure 27, Customers perception of differences compared to their acceptance rates for Charcoal Solid, shown in percentages. The letters correspond to the different plaques.

4.2. Scatter charts with tolerance limits

Based on the measured plaque values (see chapter 3.2.), a scatter chart was constructed to illustrate the distribution of all the plaques. A scatter chart is a visual representation of data points on a two-dimensional graph. It is often used to show the relationship between two variables.

Figure 28 depicts the scatter chart for the C* (chroma) and H* (hue) values, while Figure 29 portrays the scatter chart for the L* (lightness) values for Dawn. Similarly, Figure 30 showcases the scatter chart for the a* (red-green) and b* (blue-yellow) values, and Figure 31 exhibits the scatter chart for the L* values for Charcoal Solid.

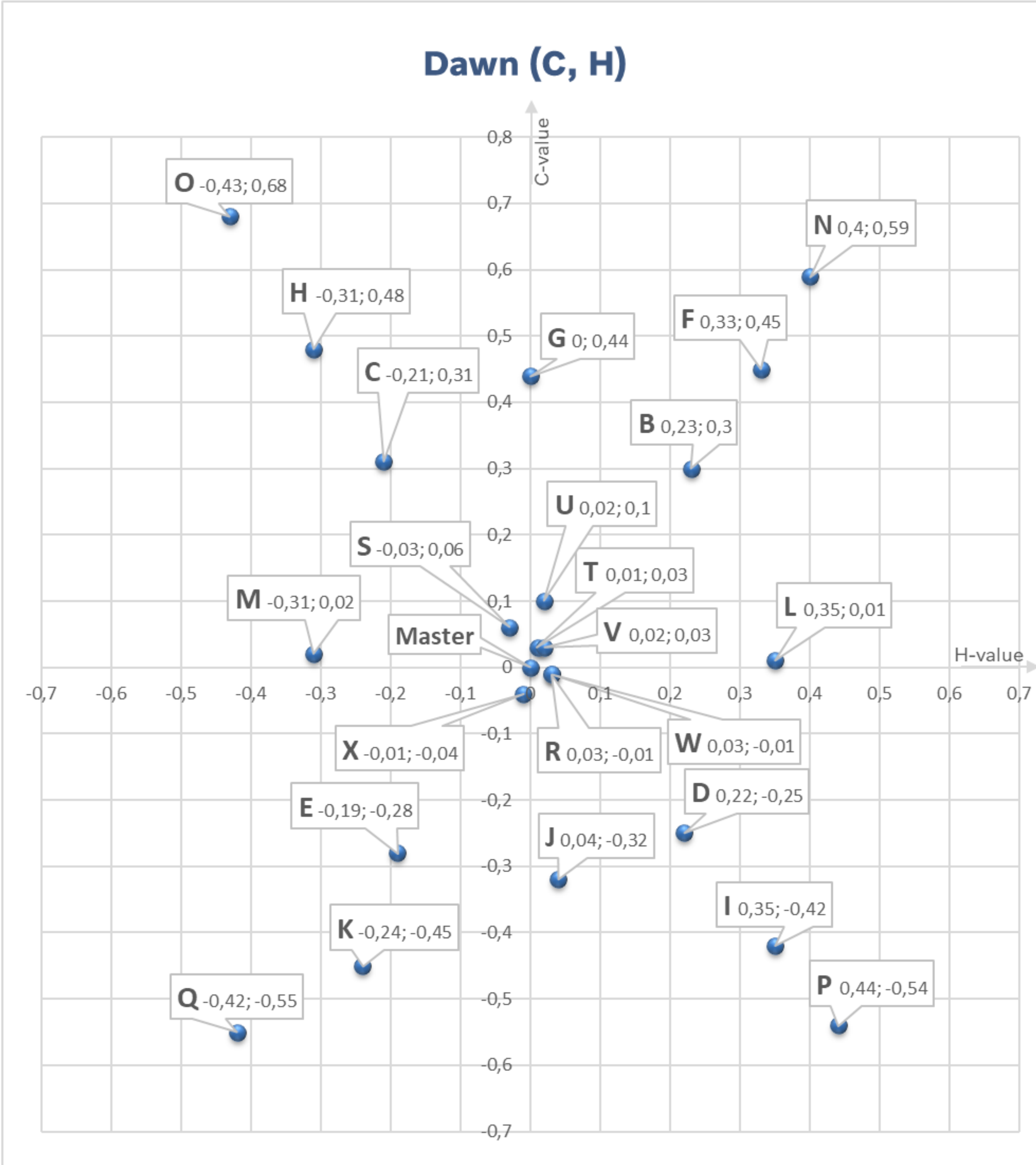


Figure 28, A scatter chart with the C and H values for the Dawn plaques.

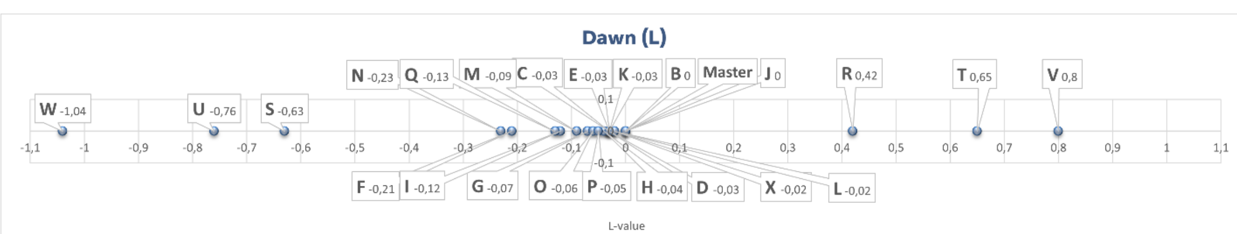


Figure 29, A scatter chart with the L values for the Dawn plaques.

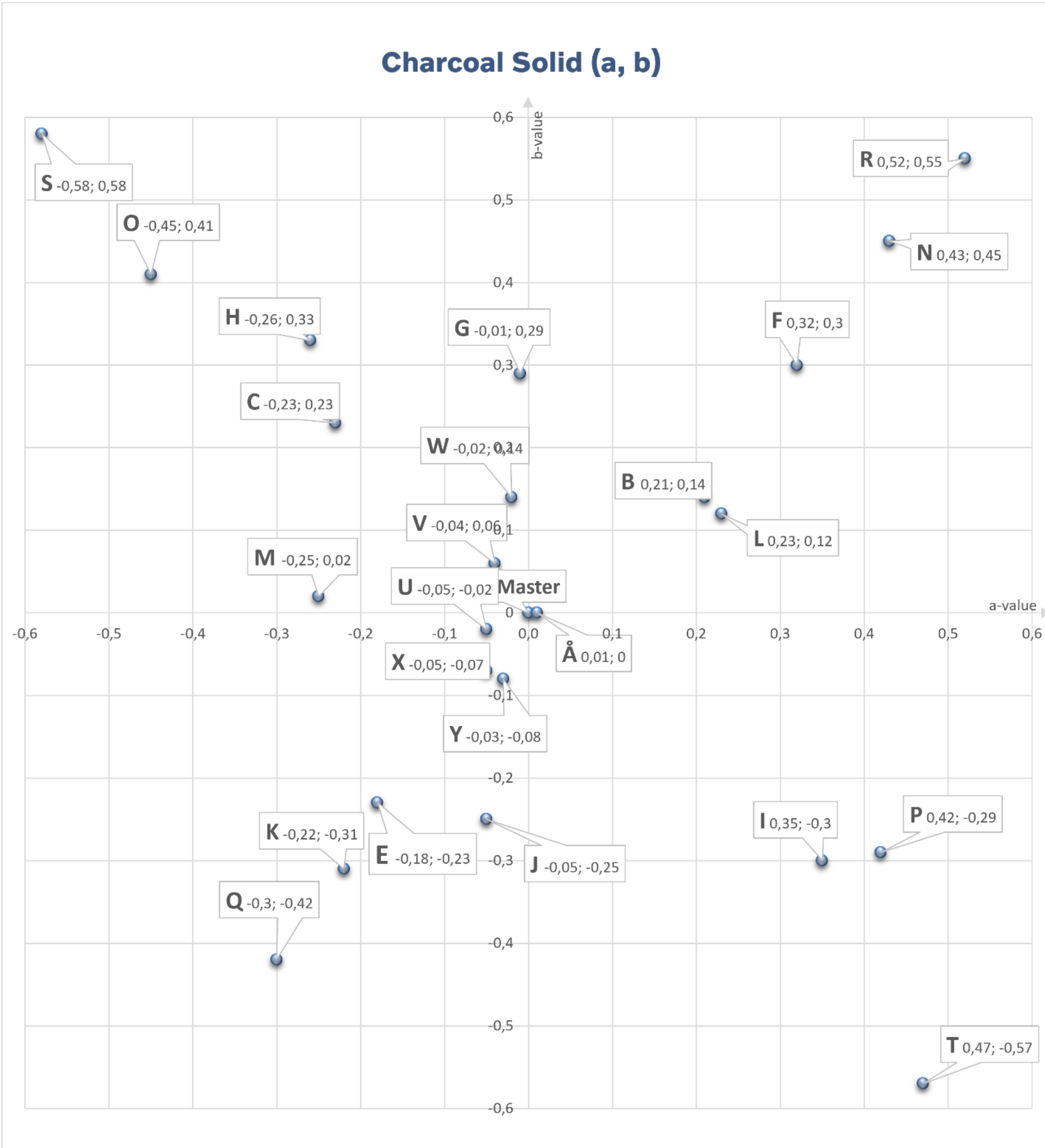


Figure 30, A scatter chart with the a and b values for the Charcoal Solid plaques.

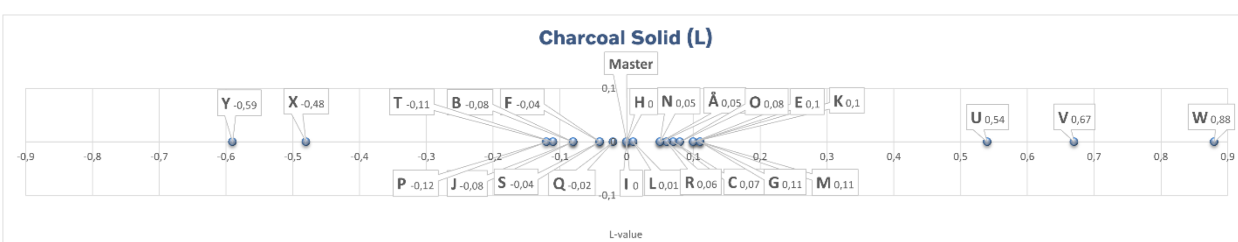


Figure 31, A scatter chart with the L values for the Charcoal Solid plaques.

To identify potential new tolerance levels, three distinct acceptance percentage values of 80%, 85%, and 90% were studied in terms of customer results. The three limits were chosen based on the brand's premium qualities and emphasis on high customer satisfaction as explained in chapter 3.2. In Figure 32, the acceptance limits for Dawn is shown and in Figure 33, the acceptance limits for Charcoal solid is shown.

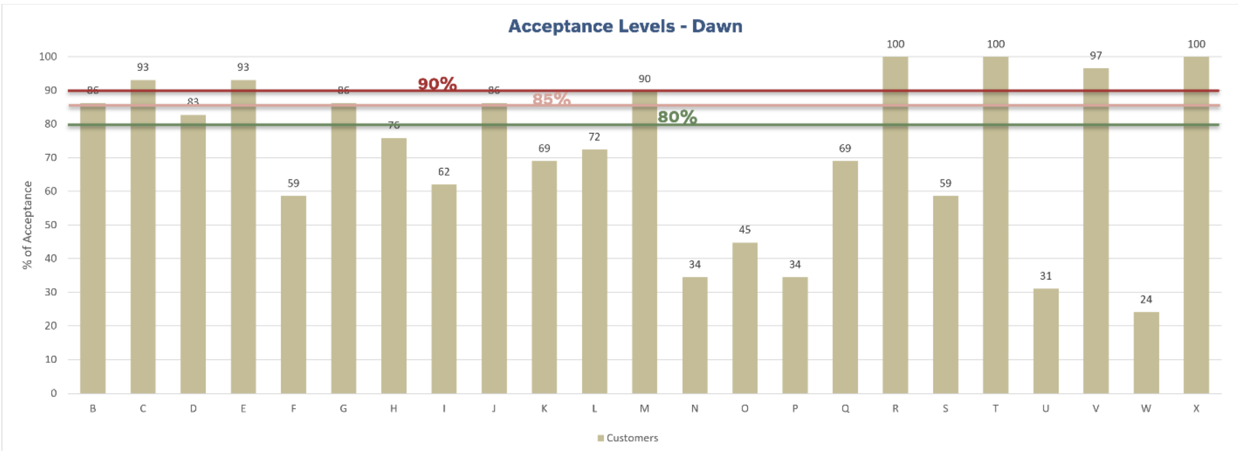


Figure 32, Acceptance levels for Dawn based on customer results. Each letter represents a plaque.

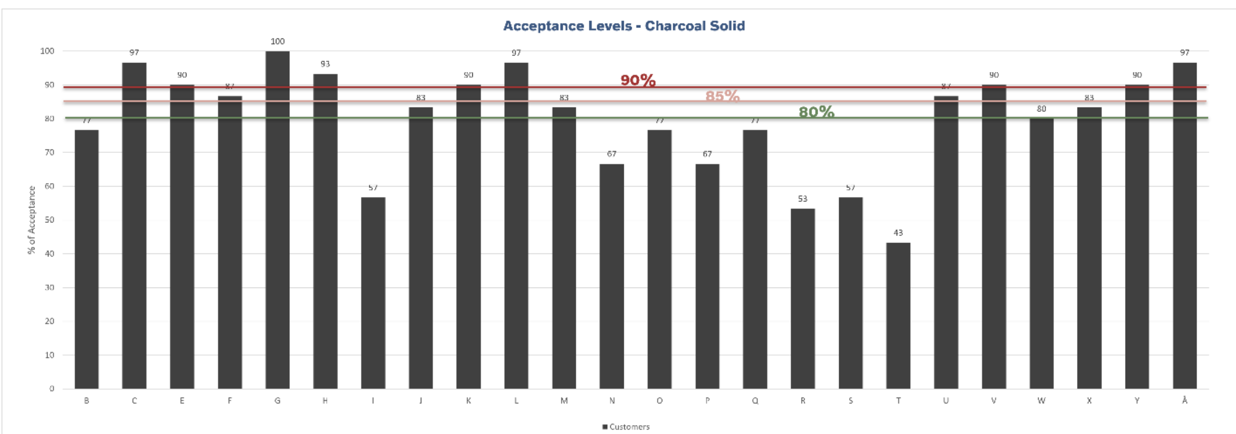


Figure 33, Acceptance levels for Charcoal Solid based on customer results. Each letter represents a plaque.

For each of the three acceptance levels, 80%, 85% and 90%, scatter charts with green rectangles representing the new tolerance levels were created, see Appendix 4. The rectangles are based on an approximation of the acceptance ratings of the plaques. Plaques which were rated acceptable by customers in the chosen interval were labeled in green. To ensure ease of implementation, the new tolerances were rounded to whole and half numbers with one decimal.

To illustrate how the scatter charts are formatted, an example is provided in the following page, see Figure 34 and 35. The Figures show the results for Dawn with an acceptance level of 80%.

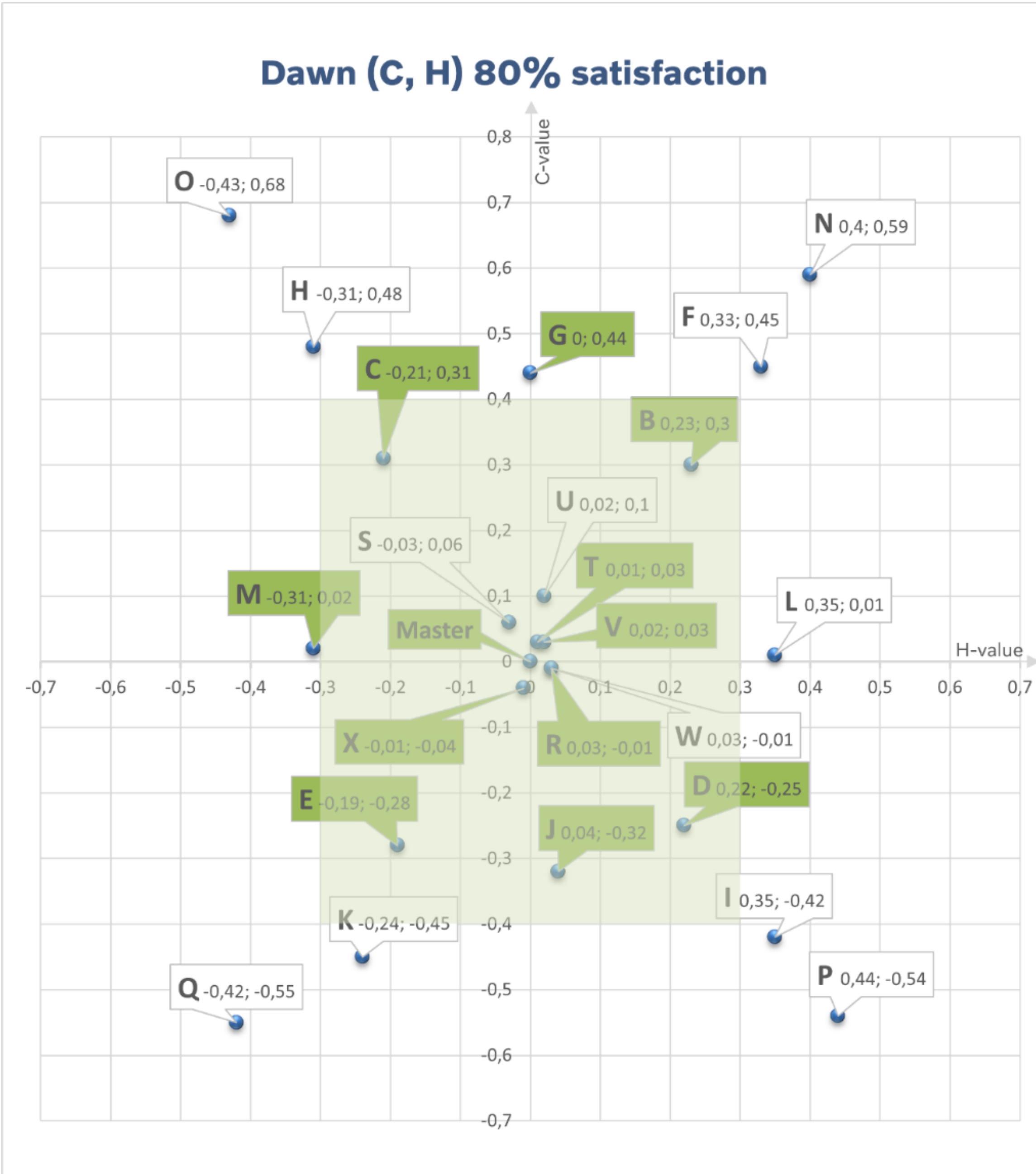


Figure 34, A chart illustrating suitable C and H tolerance limits with 80% acceptance rate for the color Dawn.

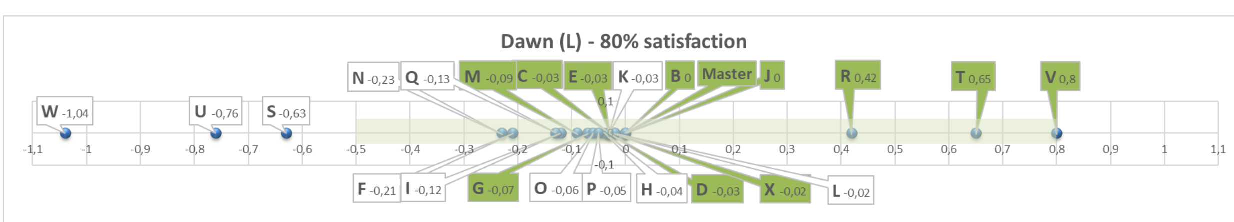


Figure 35, A chart illustrating suitable L tolerance limits with 80% acceptance rate for the color Dawn.

Upon comparison of the three new suggested tolerance limits, it can be inferred that for the color Dawn (depicted in Figure 36), the tolerances differ slightly. For 80% and 85% acceptance level, the C* value is uniform. While for 85% and 90% acceptance levels, the H* value is uniform. Furthermore, the results show that the tolerance limits for 85% and 90% are not symmetrical in positive and negative H* value. As shown in figure 36, the tolerance limits create a rectangle with greater C* value than H* value. This aligns with the findings from the theoretical studies which states that the human eye perceives differences in hue (H* value) quicker than differences in chroma (C* value). As illustrated in Figure 37 the tolerance limits for parameter L*, corresponding to acceptance rates of 80%, 85%, and 90% for the color Dawn, exhibit uniformity.

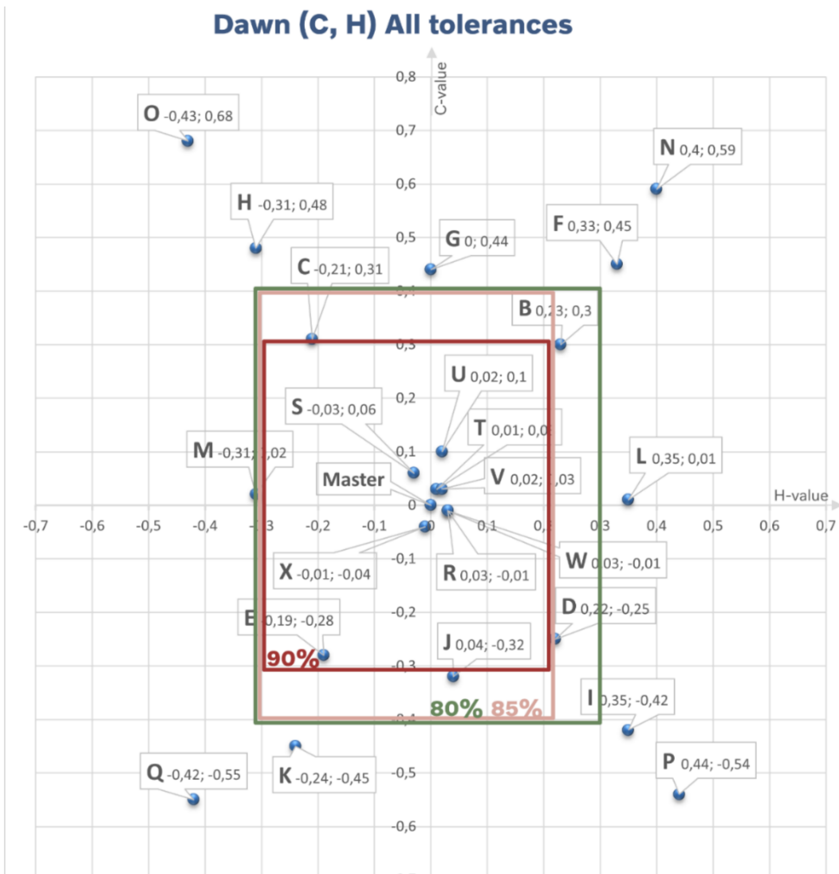


Figure 36, Chart illustration of all the different color tolerances marked out for the color Dawn (80%, 85% and 90% acceptance rates).

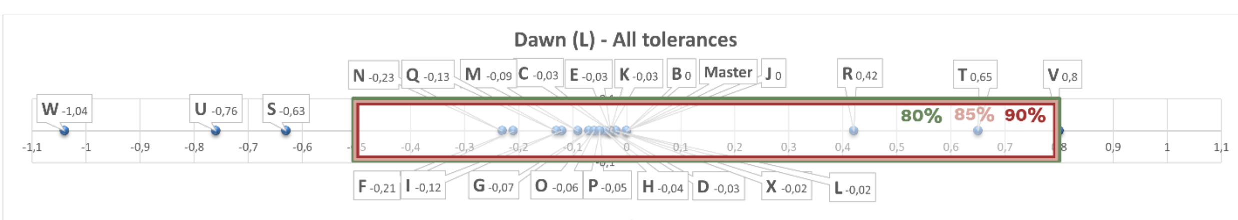


Figure 37, Chart illustrating the different color tolerances marked out for the color Dawn. The tolerances are the same for 80%, 85% and 90% customer acceptance.

After conducting a comparative analysis of the tolerance limits for the color Charcoal Solid, as depicted in Figure 38, it can be inferred that there is uniformity between the 80% and 85% acceptance rates. Furthermore, the tolerance limits for 90% are the same in b* value as for the other acceptance levels, while its a* value is slightly narrower than for the other acceptance levels. The results also show that for the L* values, the tolerance limits are uniform for the 85% and 90% acceptance levels as seen in Figure 39. For 80% acceptance level, the L* value is however somewhat larger in the positive direction. Notable here is that the L* value in negative direction is set to -0,6 for all tolerance levels. This value could possibly be extended if more plaques are tested with a lower L* value than -0,6.

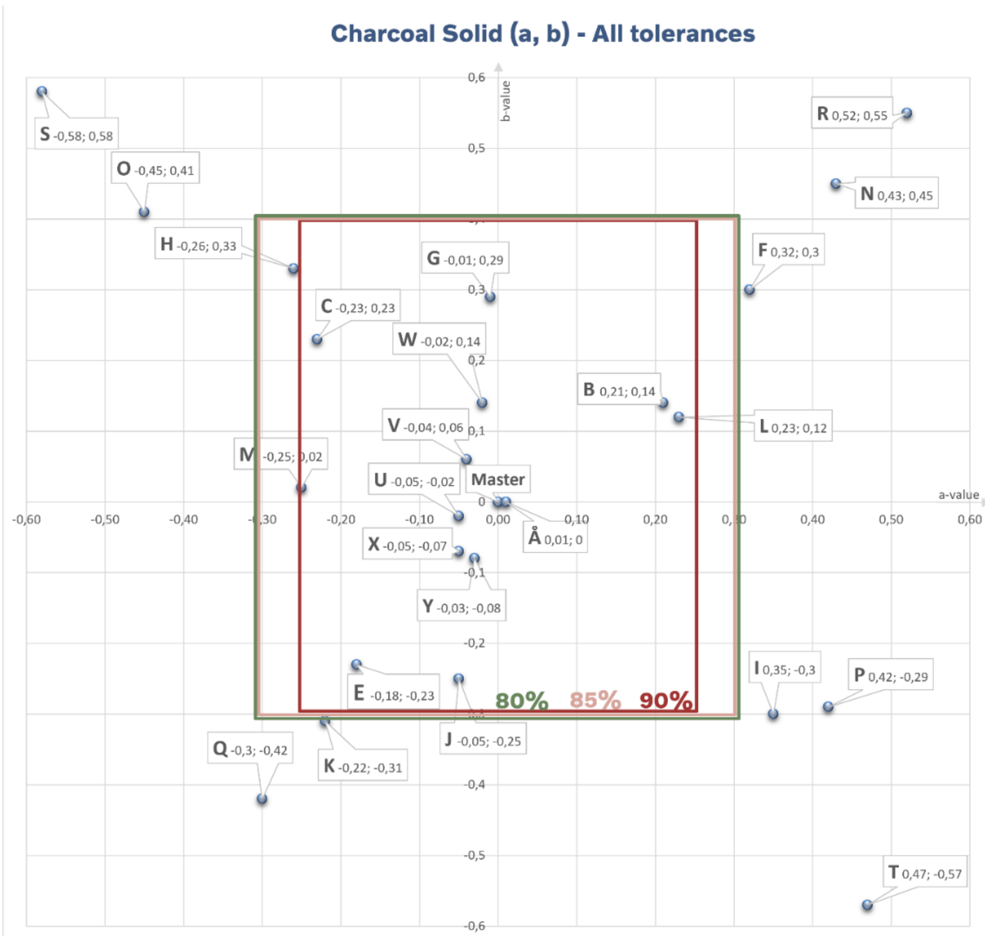


Figure 38, Chart illustrating all the different color tolerances marked out for the color Charcoal Solid (80%, 85% and 90% acceptance rates).

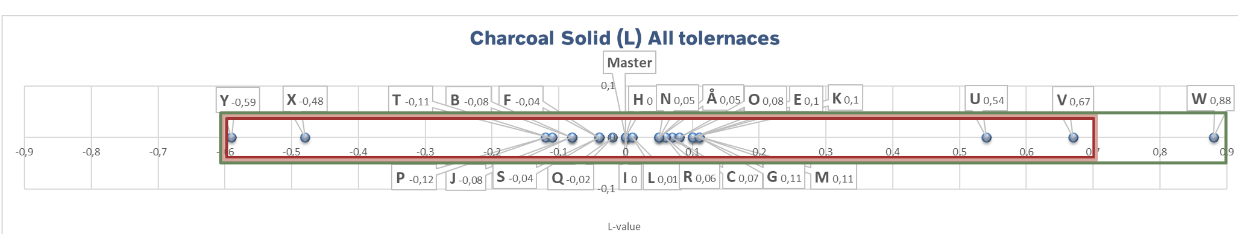


Figure 39, Chart illustrating the different color tolerances marked out for the color Charcoal Solid. The tolerances are the same for 85% and 90% customer acceptance and slightly bigger for 80%.

4.3. New color tolerance recommendations

The tolerances representing the acceptance levels for the Dawn color respectively for the Charcoal Solid color are presented in the tables 4 and 5 below. The numbers are the result of the green rectangles shown on the graphs depicted in Appendix 4.

The acceptance levels of 80%, 85%, and 90% signify the percentage of customers who would be satisfied when implementing the three different tolerance levels. These particular levels were selected to align with the requirements of a premium automotive company, emphasizing the utmost importance of achieving a high degree of customer satisfaction.

As can be seen in Table 4 and 5, the differences among the tolerance levels are not huge. When providing recommendations for tolerance levels in the context of a premium automotive company, it is crucial to uphold a high standard of customer satisfaction. This ensures that the majority of their customers are content, leading to enhanced overall satisfaction, increased customer loyalty, and a reduced necessity for costly replacements arising from color inconsistencies. To maintain the greatest level of customer satisfaction, an acceptance level of 90% should be adopted. This means that at least 90% of customers will find the color tolerances acceptable. The recommended color tolerances corresponding to a 90% customer satisfaction level are presented in the top row of Table 4 and Table 5, marked in green.

Table 4, The different color tolerances for Dawn.

Tolerance Level Dawn	**L***	**C***	**H***
90% Acceptance	+ 0,8; - 0,5	+ - 0,3	+ 0,2; - 0,3
85% Acceptance	+ 0,8; - 0,5	+ - 0,4	+ 0,2; - 0,3
85% Acceptance	+ 0,8; - 0,5	+ - 0,4	+ - 0,3

Table 5, The different color tolerances for Charcoal Solid.

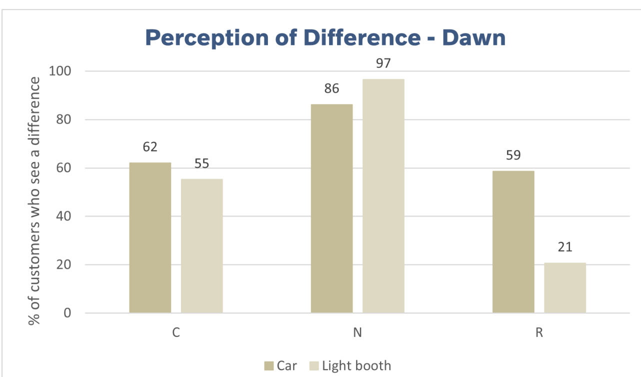
Tolerance Level Charcoal Solid	**L***	**a***	**b***
90% Acceptance	+0,7; - 0,6	+ - 0,25	+ 0,4; - 0,3
85% Acceptance	+0,7; - 0,6	+ - 0,3	+ 0,4; - 0,3
85% Acceptance	+0,9; - 0,6	+ - 0,3	+ 0,4; - 0,3

4.4. Analysis of plaques in car vs in light booth

To investigate if customers had differing opinions in the true context of the color judgement compared to a light booth, participants were instructed to assess a few plaques in a real car as well as in the light booth. For Dawn, the plaques C, N and R were chosen. For Charcoal solid, the plaques C, R and W were chosen. Of the three chosen plaques for both colors, one had a very slight difference in hue. Another was a bit more deviating in hue, and the last one deviated primarily in lightless.

Figure 40 displays the percentages of customers who perceive differences between the plaques C, N, and R and the Dawn master plaque, both when being reviewed in a car and in a light booth. It can be inferred that plaques C and N elicit similar responses, while plaque R yields a markedly different result. Specifically, a significantly greater proportion of customers perceived a difference between plaque R and the master in the car setting as opposed to the light booth setting.

Figure 40 also presents the percentages of customers who detect variances between the plaques C, R, and W and the Charcoal Solid master plaque in both car and light booth settings. Keep in mind that plaques C and R for Dawn and plaques C and R for Charcoal solid are not the same. The findings indicate that plaques C and W elicit a greater perception of difference in the car setting as opposed to the light booth, while plaque R yields the opposite effect. Specifically, the data suggests that it is more common to observe a difference in the car than in the light booth for plaque W.



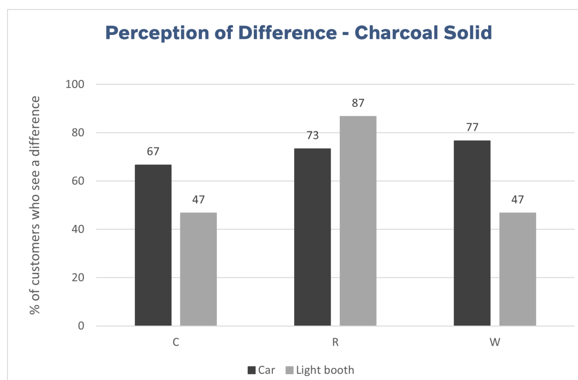


Figure 40, A bar chart illustrating percentages of customers who see a difference in the car vs in the light booth on 3 of the Dawn plaques and 3 of the Charcoal Solid plaques.

In Figure 41 the acceptance levels regarding 3 of the Dawn plaques compared to the master in both the car setting and the light booth setting can be seen. As seen both the C and R plaque is more accepted in the light both setting while the N plaque is more accepted in the car setting.

Figure 41 also illustrates the acceptance levels regarding 3 of the Charcoal Solid plaques compared to the master in both the car setting and the light booth setting. As seen both the R and W plaque is more accepted in the car setting while the C plaque is more accepted in the light booth. But the differences are only significant for plaque R.

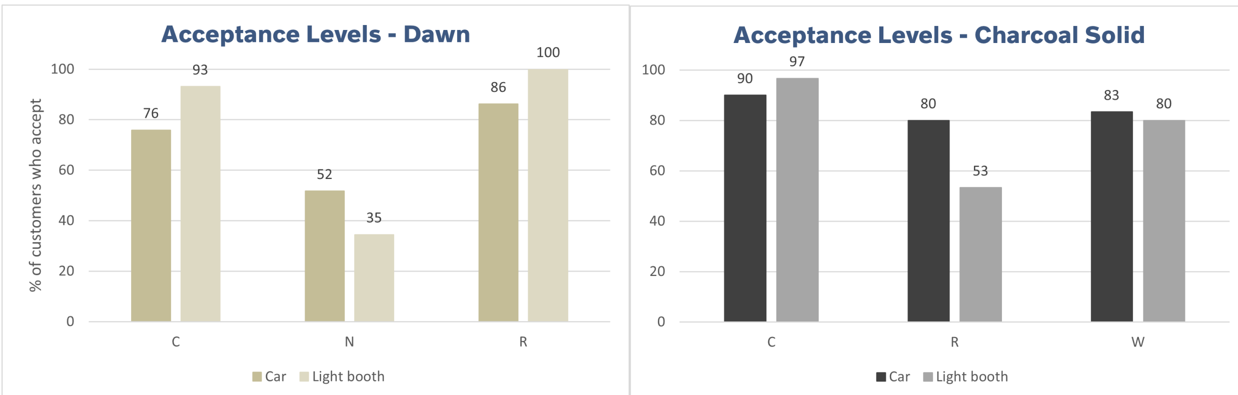


Figure 41, A bar chart illustrating percentages of customers who accept the plaque combination in the car vs in the light booth on 3 of the Dawn plaques and 3 of the Charcoal solid plaques.

To identify any potential differences in sensitivity to tolerance variations among plaque positions, the results were sorted by plaque and position. Figures 42, 43, 44 and 45 illustrate these results, with the letters representing the specific plaques, and the numbers 1, 2, and 3 indicating plaque positions as shown in Figure 46. As demonstrated in Figure 42 and 43, the position 3 exhibited the lowest percentage of participants who reported a difference for both colors, indicating that this position is relatively more difficult to discern differences on. Conversely, position 1 demonstrated the highest percentage of participants who detected a difference for the Dawn, suggesting that this position is the most sensitive to tolerance variations. While for Charcoal Solid position 2 demonstrated the highest percentage of participants who detected a difference.

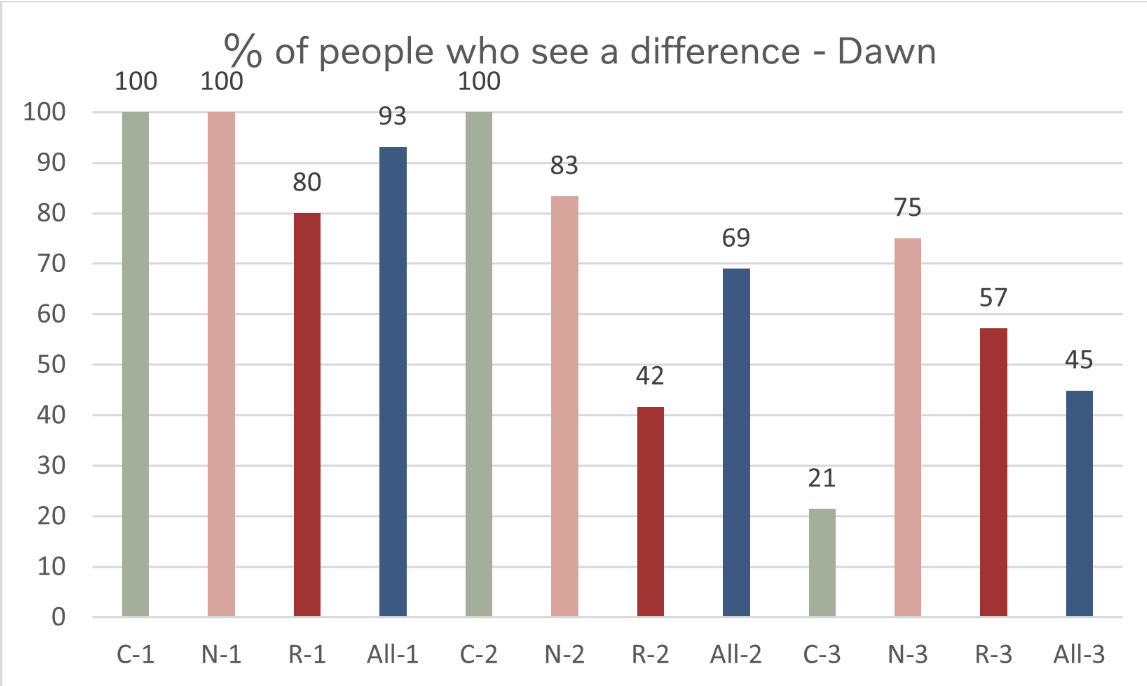


Figure 42, Percentage of people who see a difference on the Dawn plaques for each of the 3 positions in the car.

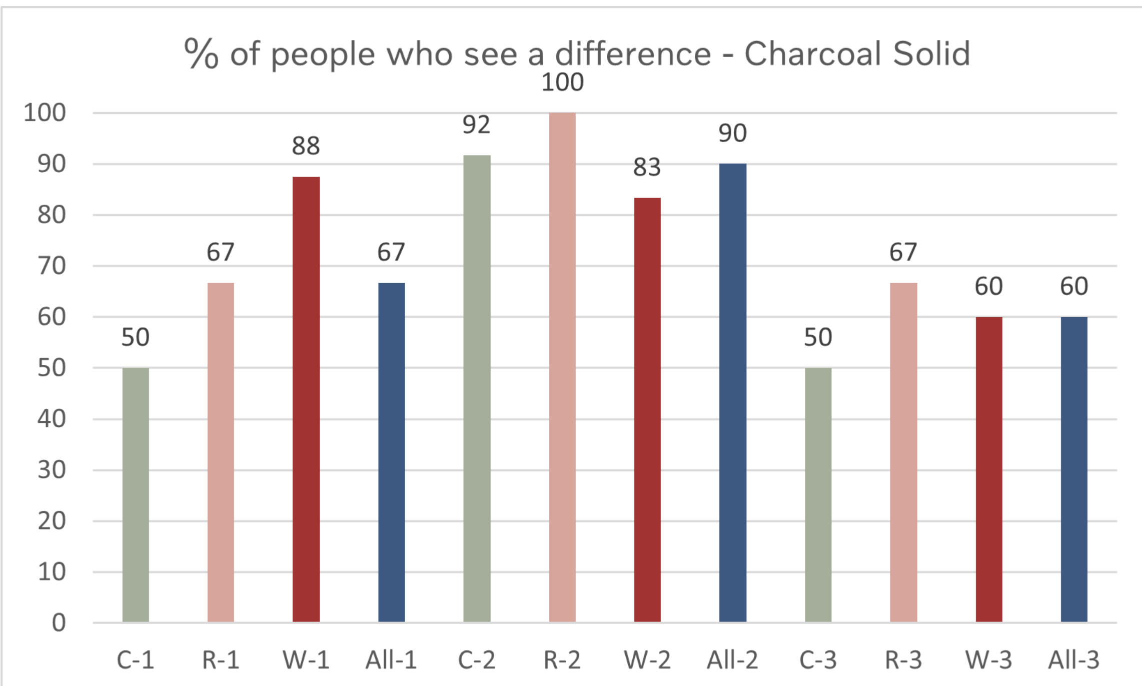


Figure 43, Percentage of people who see a difference on the Charcoal Solid plaques for each of the 3 positions in the car.

Regarding the acceptability of the color match, position 3 is considered the most acceptable for both colors, as illustrated in Figures 44 and 45. However, for the Dawn plaques, position 1 is the least accepted, making it the most critical position in terms of tolerance acceptance for this color. Conversely, for Charcoal Solid, position 2 represents the most critical position for tolerance acceptance.

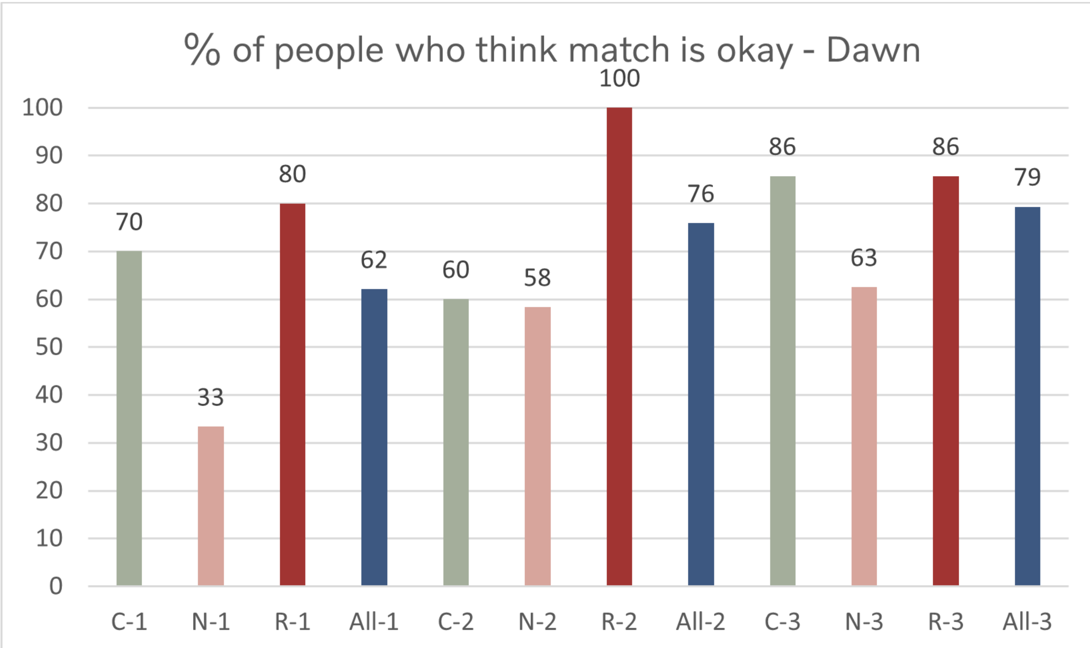


Figure 44, Percentage of people accept the match of the Dawn plaques for each of the 3 positions in the car.

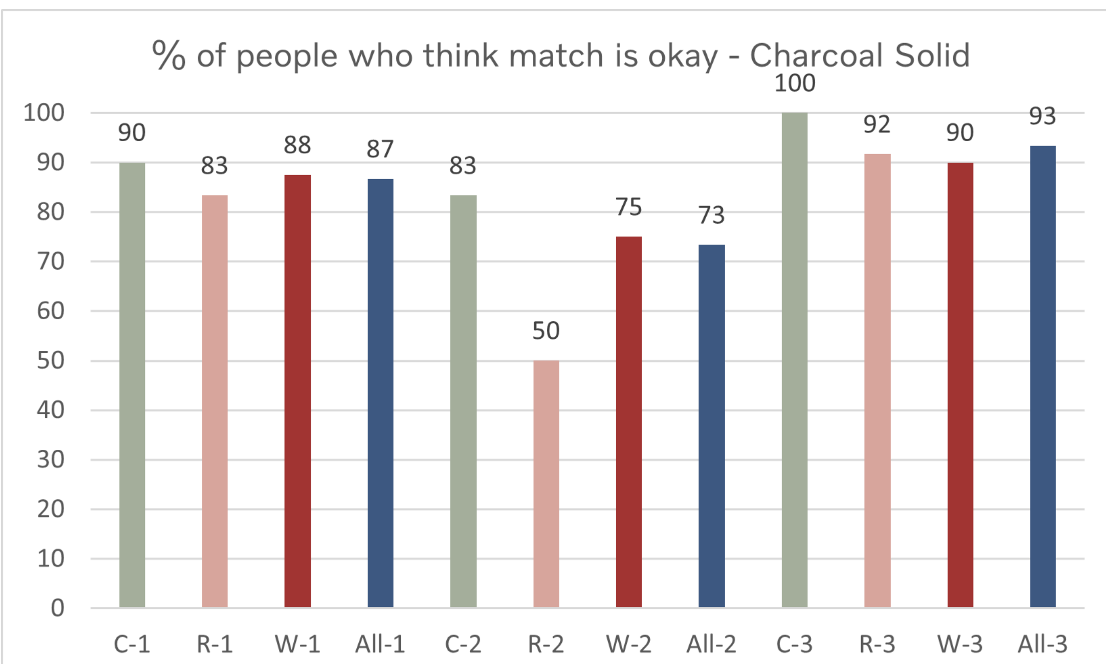


Figure 45, Percentage of people accept the match of the Charcoal Solid plaques for each of the 3 positions in the car.

Figure 46, Illustration of the plaque holder positions in the car.

4.5. Analysis of average values

When investigating tolerances in terms of acceptable variations in color, it can be interesting to explore if there are differences in user preferences and expectations based on demographic factors. For this reason, an analysis of average results was conducted for each color within three main areas: gender, car ownership and age. The topic of gender was regarded as one of the most relevant to investigate based on the following findings in color theory: Women tend to have a broader color description language than men, and men are more likely to have color vision deficiencies, such as red–green color blindness. Among the people who participated in the user studies for Dawn, 37% were women and 63% were men. Conversely, among the people who participated in the user studies for Charcoal Solid, 63% were women and 37% were men.

Overall, by comparing the results between different demographic groups, you can gain insights into how these factors may affect user preferences and expectations for acceptable color variations in car interiors.

The result of the analysis for Dawn is presented in Figures 47, and 48. It shows that there is no significant difference between males and females, car owners and non-car owners as well as between the three different age spans.

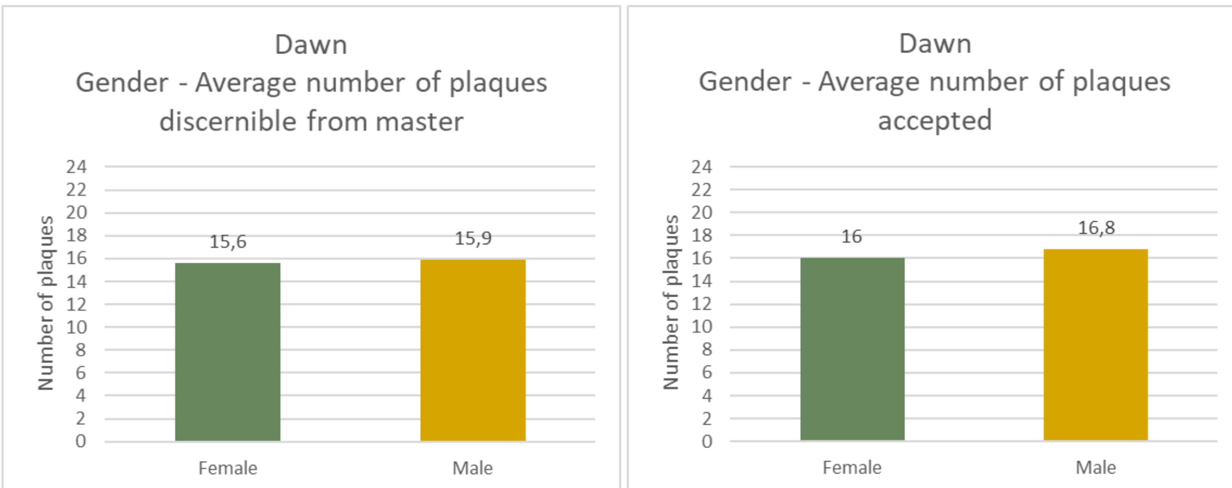


Figure 47, Average results for Dawn - Gender

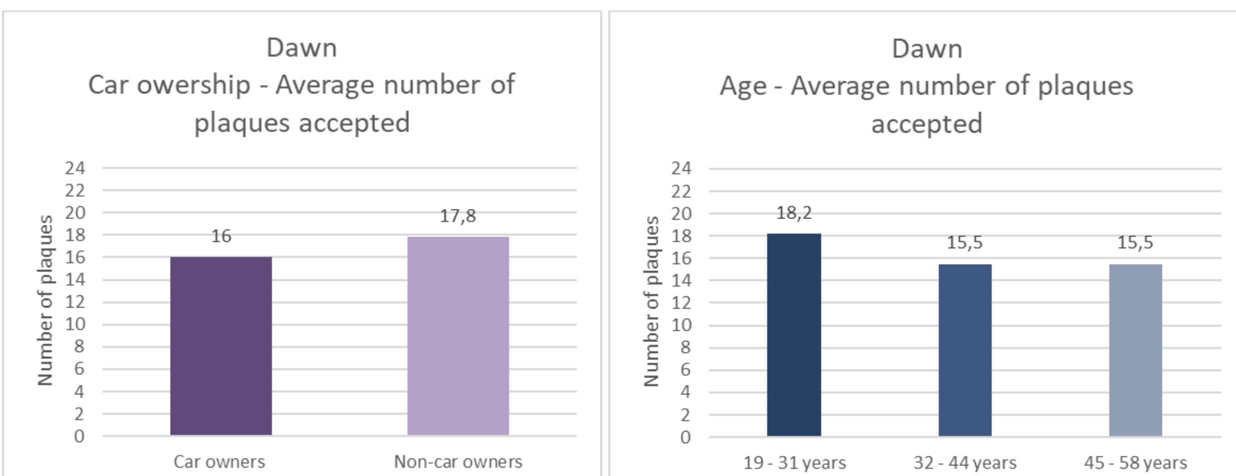


Figure 48, Average results for Dawn - Car ownership and age.

In the same manner, the result of the analysis for Charcoal Solid is presented in Figures 49, and 50. As with Dawn, the data shows that there is no significant difference in acceptance between males and females, car owners and non-car owners as well as between the three different age spans.

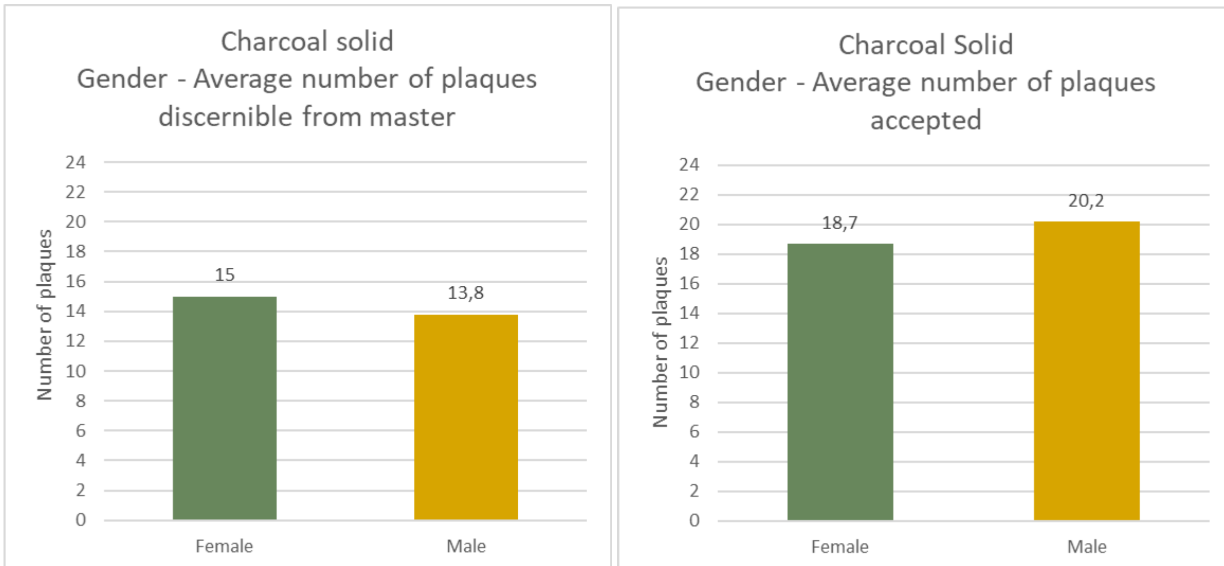


Figure 49, Average results for Charcoal Solid – Gender.

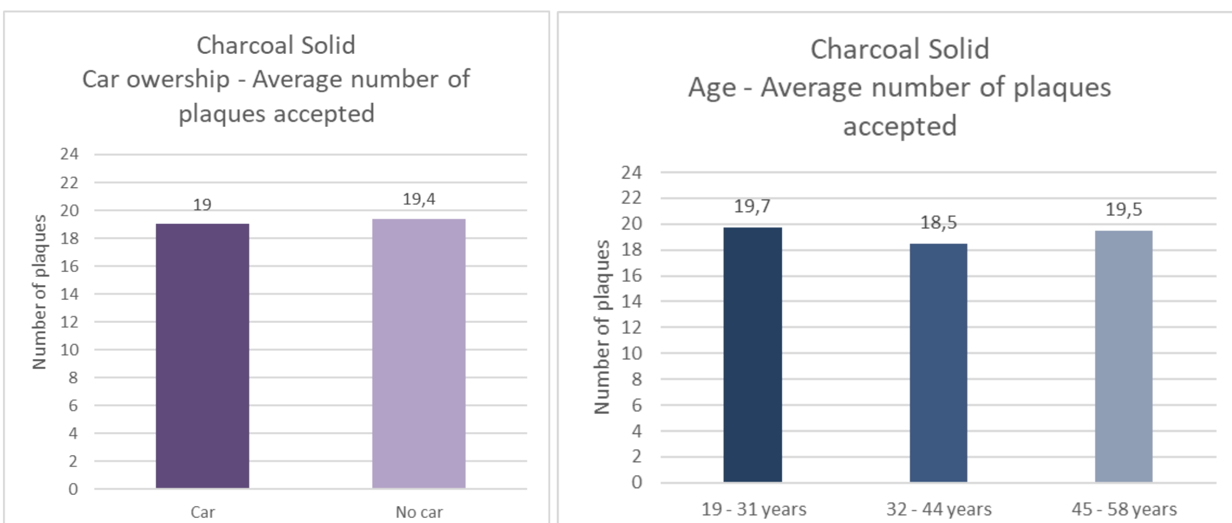


Figure 50, Average results for Charcoal Solid - Car ownership and age.

4.6. Comparison with ΔE00 tolerances

During the measurement of plaques, the ΔE00 values (see chapter 2.3 for explanation of ΔE00) were computed and subsequently presented in ascending order in Table 6. These values were then compared against the three customer acceptance levels, 80%, 85%, and 90%. Based on their respective tolerances, the approved plaques were marked in green. It is evident that the probability of plaque approval increases with decreasing ΔE00 values. However, a clear correlation between ΔE00 values and plaque approval is absent, as not all plaques with a certain ΔE00 value are approved. This indicates that the ΔE00 value may not be an accurate representation of customers' opinions. For instance, plaque X for Charcoal Solid, which has a low ΔE00 value, is not approved by customers with an acceptance level of 85% or higher, whereas plaque H, with a much higher ΔE00 value than plaque X, is approved for acceptance levels of 80% and higher. Therefore, it can be concluded that the ΔE00 value does not precisely reflect customers' opinions.

Table 6, The ΔE00 values compared to the different tolerances (80%, 85% and 90% customer acceptance). The approved plaques are marked in green.

Dawn (approved plaques marked in green)					**Charcoal Solid** (approved plaques marked in green)				
	ΔE00	**80%**	**85%**	**90%**		**ΔE00**	**80%**	**85%**	**90%**
A					A				
X					Å				
R	0,18				X	0,21			
T	0,26				U	0,22			
S	0,27				Y	0,24			
J	0,28				J	0,25			
U	0,32				V	0,26			
V	0,33				G	0,29			
D	0,37				B	0,34			
E	0,38				E	0,35			
G	0,38				W	0,36			
C	0,4				L	0,37			
W	0,43				M	0,37			
B	0,44				C	0,41			
M	0,46				K	0,44			
L	0,5				H	0,51			
K	0,54				F	0,57			
I	0,6				I	0,59			
H	0,61				Q	0,59			
F	0,65				P	0,69			
P	0,75				N	0,78			
Q	0,78				O	0,78			
N	0,8				T	0,89			
	0,85				R	0,95			
					S	1,02			

5

DESIGN RECOMMENDATIONS

This chapter presents a set of design recommendations derived from a synthesis of theoretical perspectives, interviews, and user testing results. These recommendations are intended to guide the design of automotive interiors, particularly with respect to color tolerances, in a more acceptable manner for customers when dealing with differences in color.

5.1. Design recommendations

Based on the insights gathered from interviews with designers, color experts and engineers at VCC, as well as user tests and theoretical studies, design recommendations have been formulated. The objective of these recommendations is to enhance the design's capacity to accommodate color variations, thus enabling larger tolerance limits.

An important design recommendation identified during this project is to incorporate transition details between two different materials, which can make color differences between them more acceptable. Additionally, such details can serve as a visual focus, detracting attention from any color differences. This is demonstrated in Figure 51. Another crucial design recommendation is to embrace greater color variation instead of uniformity, as this will also contribute to a more forgiving appearance, as illustrated in Figure 51. However, this should be done with caution as to not create an unharmonious appearance. Lastly, materials that possess greater structural complexity can also be more accommodating toward color tolerances.

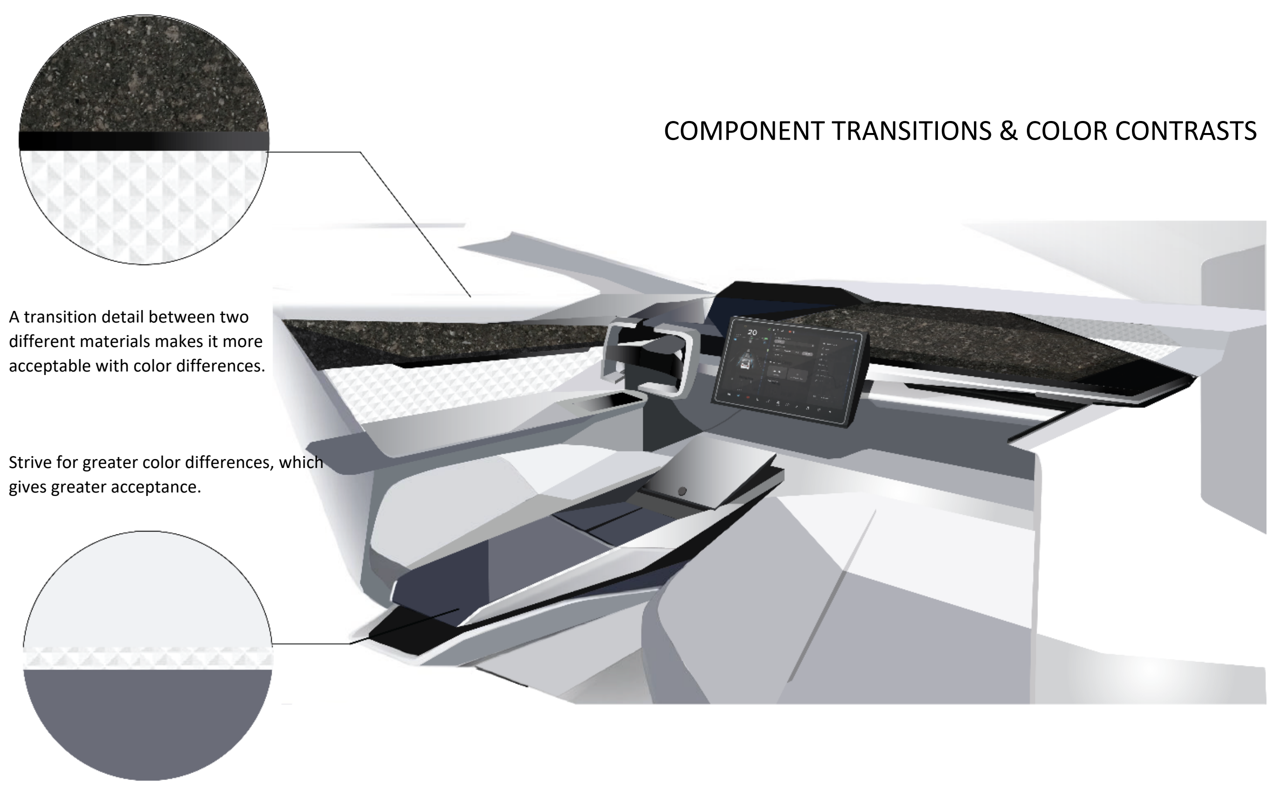


Figure 51, Illustration of design recommendations. In the figure transition details between different materials can be seen as well as greater color differences between components.

Additionally, careful consideration should be given to the selection of colors. Colors that are situated close to the different axis in the color sphere are more sensitive to color differences, while those that are more distant from the axis exhibit greater tolerance toward such differences.

Furthermore, when choosing a color, one should also consider its placement in the color sphere based on the ellipsoids which represents the perceived area of acceptance, as show in Figure 52. This is largely because the eye's sensitivity to differences in hue depends on the color's placement in the color sphere. For example, differences in orange hues are easier to notice than differences in blue-green hues. In other words, choosing color wisely can help keep appearances uniform.

More information on the theory surrounding the color wheel illustrated in the Figure 52 can be found in chapter 2.2. in the section on "Human perception of color variation".

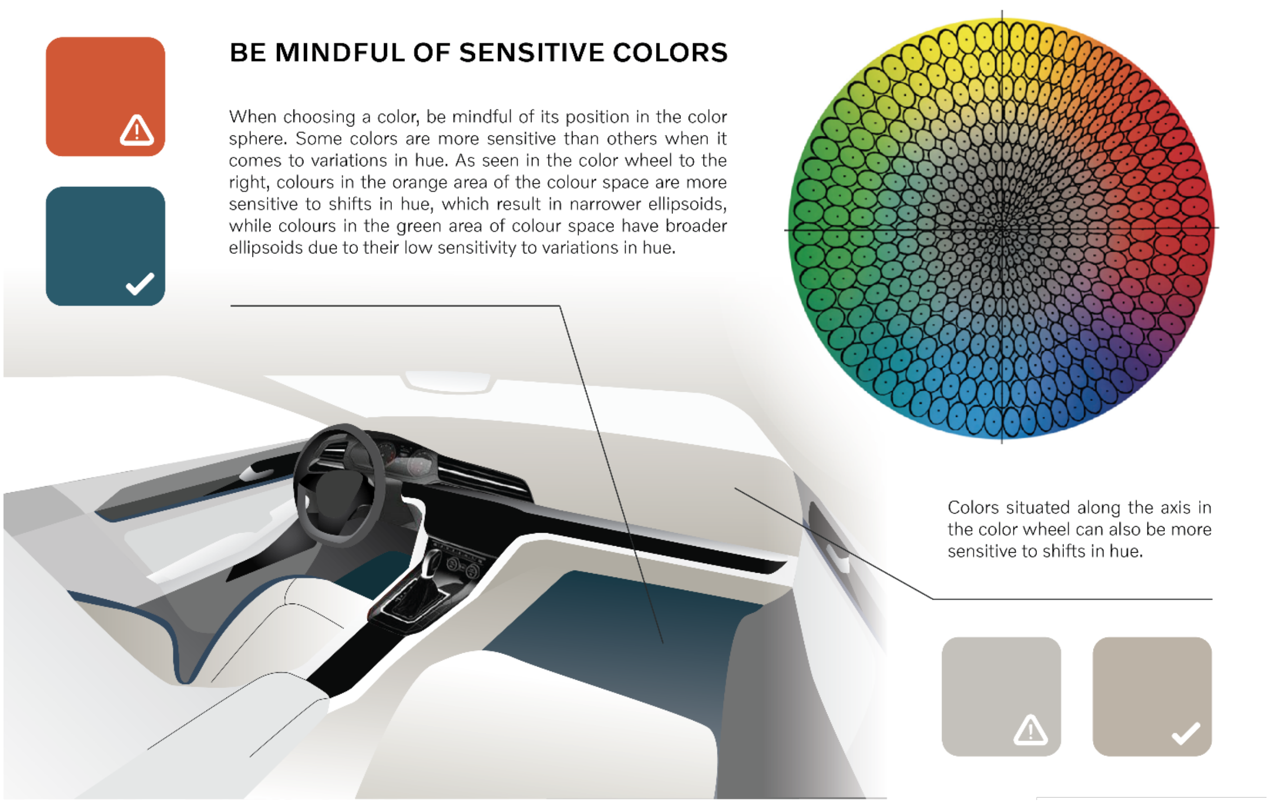


Figure 52 Illustration of design recommendations. The figure shows what to keep in mind regarding color choices.

6

DISCUSSION

This chapter discusses the process and findings presented in the previous chapters. The results are analyzed, and their implications explored, contributing to the existing knowledge in the field. By addressing the research objectives, evaluating strengths and limitations, this chapter offers valuable insights and conclusions.

6.1. Discussion regarding user tests

Below follows a discussion regarding an interesting topic related to the user tests and possible sources of error.

Only Volvo-employees participated in the tests, could be biased

Because of the limitation that the study had to be conducted with the light booth PQ uses to assess components, the user test could only be conducted at Volvo Cars office in Gothenburg. As a result of this, only Volvo-employees conducted the tests. This group of people mostly consisted of engineers in various fields. Although no people with color-assessment related occupations were allowed to participate (aside from the expert group), Volvo employees might be biased or affected by their jobs when conducting the study. To acquire a more diverse group of people, it would have been beneficial to include people who are not Volvo-employees as well.

People might be wearing color-blocking glasses without knowing it

Several of the people who participated in the user tests wore glasses. Some of these participants could not say with certainty if their glasses were blue-light-blocking, which could impact their result. Although it is a contested subject, blue-light-blocking glasses are claimed to reduce the amount of blue light that reaches the eye. In other words, these types of glasses could potentially hinder the participant from seeing the full spectrum of colors.

Only one type of light source used

The standardized light source D65 (simulated daylight) was the only light source used during the tests in this study. As mentioned in the theory chapter, colors are perceived different depending on the light. The results could therefore theoretically differ if another light source would have been used. Since cars are used in a large variety of light conditions, it would be beneficial for the study if several light conditions were tested with the participants and used for the analysis. However, allowing the participants to judge each plaque in a range of different light sources would certainly increase the amount of time needed for each test by quite a lot. Because of this, the decision was made to limit the light sources to only one in this study, D65.

Plaques are handled continuously, their finish and color could be impacted

When plaques are being handled their appearance may be affected. A color expert from Konica Minolta, has observed that plaques handled by hand may display color differences of up to 0.1 when measuring with L*a*b* or L*C*H*. This variation in color could be significant when evaluating accurate color matching.

To minimize this risk, cotton gloves have been worn at all times when using the plaques. However, the constant handling and contact with various surfaces during the user tests could have impacted their finish and color over time. The impact is probably not significant, but because of this, it is difficult to say if each person who viewed the plaques got the same exact conditions with absolute certainty. The difference is likely to have been the biggest between the first test participant, who saw the plaques in their most “unhandled” condition, and the last test participant who saw the plaques in their most “handled” condition.

Difficult to imagine a plaque as a real component in a car

The user tests were designed in a way that was meant to help the participants understand the true context of the color-judgement, in other words, the interior of a car. Although it had to be done in a very controlled environment.

In the first part of the test, the participants were seated in a car with an interior corresponding to the color they would be judging, i.e., a light beige interior for Dawn and a dark grey/black interior for Charcoal Solid. In the car, they were given demonstrations of how components could be situated that were supposed to “match” color wise. Once it was time to judge the plaques in a light booth, the participants were urged to imagine that the plaques represented “real” components in order for them to give a realistic answer. Naturally, it could be quite difficult to imagine a plaque as a real component in a car, as it does not imitate the true size and shape of the component. It also does not indicate where in the car it would be situated. For this reason, the result of the study might not exactly reflect the true opinions of the participants.

Plaques do not cover all surface areas in grid

The plaques utilized in the study were arranged in a cross pattern when plotted in a graph, as illustrated in Figure 53. In order to more effectively analyze and discern differences along each coordinate axis when utilizing the L*a*b* or L*C*H* color system, it could be advantageous to arrange the plaques in a different cross pattern, as depicted in Figure 54. This would enable a more straightforward and thorough examination of color tolerances in each individual axis. However, the cross pattern used in the study aids in examining the outermost corners of the tolerance boxes.

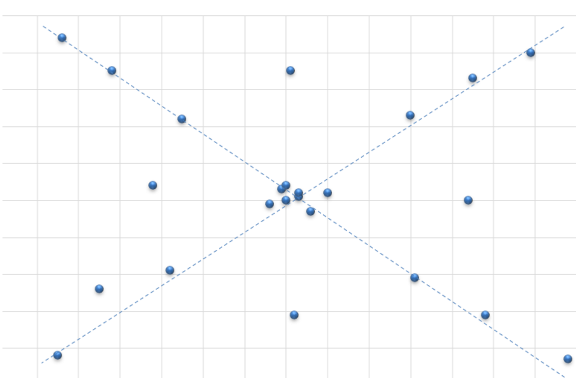


Figure 54, The plaques used in the study in a chart illustrating their positions.

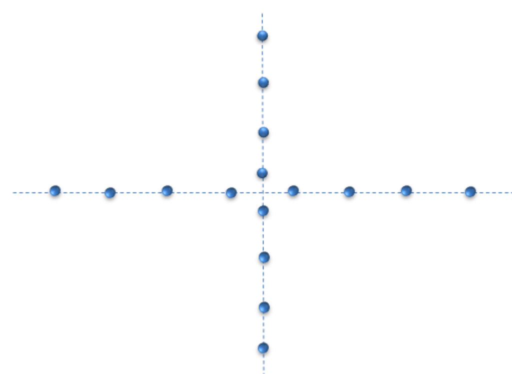


Figure 53, Illustration of a different pattern for the plaques.

Plaques should have been measured in several areas

The plaques were subjected to a single measurement using a spectrophotometer, which may not have accounted for potential variations across different regions of the plaque. Employing multiple measurements across diverse spots and deriving an average value would have resulted in a more accurate representation of the overall plaque appearance. The measured surface area was about 7 cm², which may have been inadequate to capture the entirety of the plaque's color (measuring 7,8 x 4,6 cm). The choice of measurement technique could have impacted the findings, given the utilization of the measured value in result analysis.

Plaque defects

Upon inspection, it was noted that some of the plaques had slight defects on the surface of the material. The problem was most apparent for Charcoal Solid where several of the plaques had a lighter streak on one side of the plaque, see Figure 55. A few of the plaques also had small indentations or marks and slightly uneven coloring. Naturally, these imperfections could have impacted the overall judgement made by the participants.

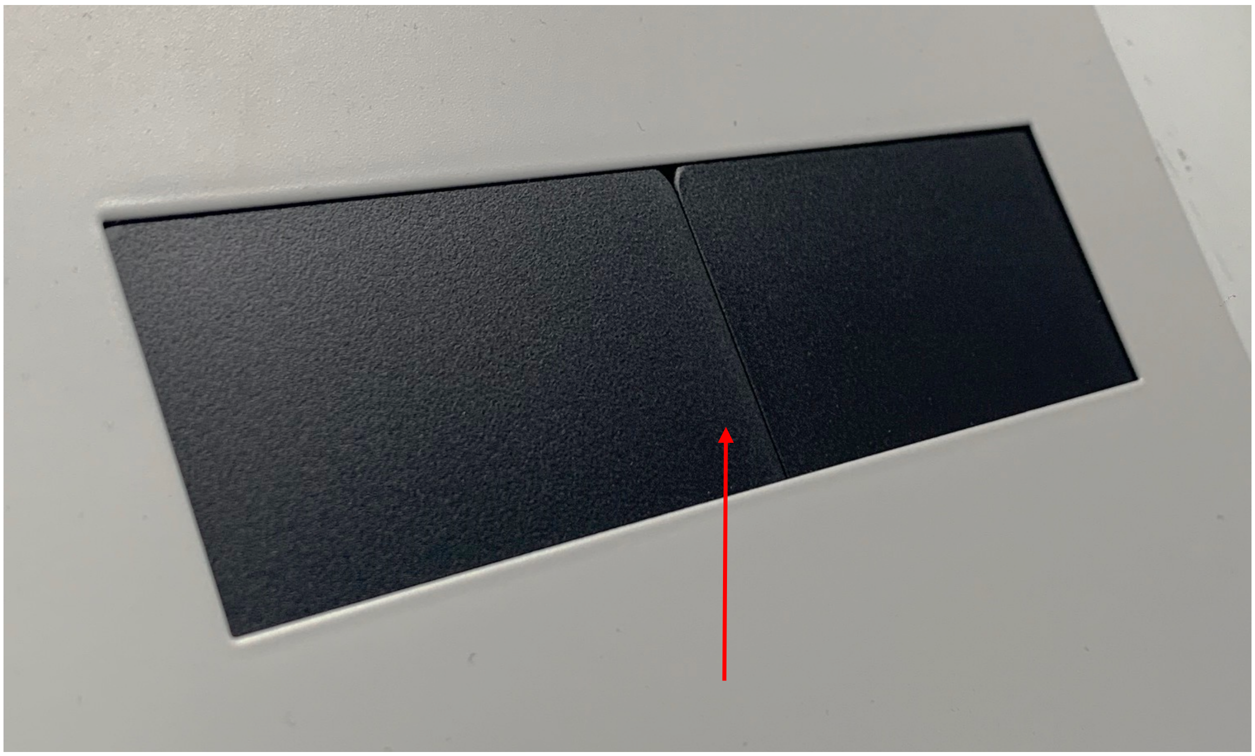


Figure 55, Defect on a Charcoal Solid plaque. The left one has a lighter streak on the right side of the plaque.

6.2. Discussion regarding results

Below follows a discussion regarding interesting topics related to the results of the study.

Experts more critical than customers

Based on the findings of the user study, it is evident that color experts demonstrate significantly higher levels of discernment when evaluating color tolerances compared to customers. The experts consistently detect discrepancies more frequently than customers and expresses a greater degree of dissatisfaction with color combinations. This distinction can potentially be attributed to the color experts' specialized training and experience in identifying color variations, which renders them more adept at this task compared to the average customer. Additionally, it is likely that the experts approached the user test with a conscious awareness of their role in identifying differences, prompting them to adopt a heightened critical stance towards assessing color tolerances. Consequently, it is possible that the experts perceived discrepancies where none were noticeable. Nevertheless, the results clearly indicate that the experts employ a markedly more critical evaluation of color tolerances than customers.

Results shown in 3 different acceptance levels

The results obtained from the user study are presented in three distinct levels of customer acceptance. The primary objective of the user study was to determine the limits of color tolerance among customers, which means that the presented tolerance limits are solely based on customer opinions and not those of experts. It was deemed necessary to present the results in three different levels of customer acceptance to clearly illustrate the variations in requirements depending on the level of customer satisfaction. As a premium automotive company, VCC aims to uphold high levels of customer satisfaction, and therefore the requirements need to align accordingly.

There is no definitive benchmark for determining the precise level of customer satisfaction that should be achieved. Hence, three different levels are presented, namely 80%, 85%, and 90% customer satisfaction. Considering the high price-point for Volvo cars and the brands emphasis on premium quality, high customer satisfaction is key. This is why the decision was made to not investigate anything lower than possibly 80%. 95% was also considered as an acceptance level, however, from the data in the user tests it was noted that only three plaques would be approved with 95% acceptance (both for Dawn and Charcoal Solid). This would create a tolerance box that is basically non-existent. For this reason, 95% was not chosen as an acceptance level.

The position of a component within the car can influence the requirements, as customers tend to be more critical of components that are prominently visible compared to those that are more concealed. Consequently, the established acceptance limits can be appropriately utilized for different positions within the car, with the highest level of customer acceptance applied to the most visible components, for instance.

The new tolerances only apply to the examined colors in this study, Dawn and Charcoal Solid

The user study focused on the examination of two distinct colors, namely Dawn and Charcoal Solid. It is important to note that color tolerances vary for each specific color, influenced by its position within the color sphere. As stated in chapter 2.2., the eye's sensitivity to differences in hue depends on the color's placement in the color sphere. This can be effectively demonstrated by representing the tolerances as ellipsoids of varying sizes. Consequently, the tolerance requirements applicable to one color cannot be directly translated or applied to another color. The results obtained from this user study are therefore only applicable to the specific colors that were examined in the conducted tests.

Result aligns with findings in color theory

Regarding the credibility and reliability of the results from the user study on color tolerances, it can be said that the result aligns well with the findings made in color theory. In the new tolerance recommendations provided in chapter 4.3. for Dawn, it is clear that the individual values for each axis should not be of equal size. The lightness (L*) value allows the greatest tolerance limits, followed by slightly narrower limits for the chroma (C*) value. Lastly, the hue (H*) value holds the narrowest tolerance limits. This coincides well with findings in literature on color theory which claims that the human eye does not detect differences in hue, chroma and lightness equally. In fact, the average observer will see a difference in hue first, chroma second and lightness last, just as the new recommendations are modeled.

Similarly, for Charcoal Solid, the new tolerance recommendations provided in chapter 4.3. also allow the greatest limits for the lightness (L*) value. However, Charcoal Solid is modeled with the L*a*b* system rather than L*C*H* as for Dawn. The a* value (red-green) and b* value (yellow-blue) both represent shifts in hue rather than hue and chroma as for Dawn. In other words, the a* and b* tolerance values should be quite similar according to theory, which coincides well with the new recommendations provided in chapter 4.3., except for the 90% acceptance level where the b*value is slightly larger than the a* value.

6.3. Discussion regarding the project from an ethical and sustainable perspective

Below follows a discussion regarding interesting topics related to ethics and sustainability.

The project from an ethical viewpoint

During the user tests, an ethical dilemma arose concerning the use of a color vision test conducted by all participants at the beginning of the study. With participants who scored poorly on the test (indicating significant color vision impairments) having their responses individually examined to determine if they seemed reliable. In one case, a participant was excluded based on this criterion. While it can be argued that excluding individuals based on color vision impairments is ethically questionable and that all perspectives should be included. But the specific objective of the test was to assess color discrimination abilities in individuals with normal color vision. A colorblind participant could potentially confound the results and undermine the intended objectives of the test. In order to maintain the test's validity and ensure accurate interpretation of the outcomes, it was deemed appropriate to exclude participants with color vision impairments in such cases.

The ethical model that can be connected to the described situation is Utilitarianism. Utilitarianism focuses on maximizing overall utility or happiness for the greatest number of people. In this case, the decision to exclude participants with significant color vision impairments from the study can be seen as aligning with a utilitarian perspective. By excluding these individuals, the results are more likely to accurately represent the color vision abilities of the broader population, maximizing the utility of the study's findings for a larger audience. While it may raise ethical concerns about inclusivity and fairness, the decision is made based on the overall benefit to the study's validity and the broader impact it aims to achieve.

The project from a sustainable viewpoint

The motivation behind this project stems from the increasing adoption of sustainable materials in the automotive industry, which has posed challenges in meeting existing color tolerance standards due to the inherent complexities associated with these materials. As a result, this project aimed to address this issue by establishing customer-centric tolerance requirements that are more tolerant compared to the prevailing standards. The findings of this project therefore offer valuable insights to the automotive industry, facilitating the enhanced and simplified utilization of sustainable materials.

6.4. Summary of discussion

The discussion covers key points regarding the user tests. It discusses potential sources of errors like that the tests were conducted solely with Volvo employees, which may introduce bias. While acknowledging the need for a more diverse participant group, it suggests that Volvo employees still offer valuable insights. The results reveal that color experts exhibit higher discernment and dissatisfaction compared to customers. The study presents acceptance limits at different satisfaction levels and emphasizes that they only apply to the examined colors. Additionally, it discusses ethical considerations related to excluding participants with color vision impairments and highlights the project's aim to address color tolerance challenges in sustainable materials for the automotive industry.

7

CONCLUSION

The conclusion chapter summarizes the key findings and insights of the research project, reflects on its implications for theory and practice, and offers recommendations for future research. It draws together the main arguments and contributions of the study and provides potential avenues for further exploration.

7.1. Conclusions on color tolerances

The following section presents the conclusions drawn regarding color tolerances based on the comprehensive analysis of theoretical foundations, empirical results, and in-depth analysis conducted in this study.

- How can requirements regarding color tolerances in interior car components be modeled so that they correspond to the customers' expectations?

The study findings demonstrate that color tolerances vary depending on the specific color and its position within the color sphere, since the eye's sensitivity to differences in hue depends on the color's placement in the color sphere. The results derived from the user tests indicate that appropriate color tolerances should be represented in a rectangular manner for ease of implementation. The rectangles follow two axes in a graph corresponding to either hue-, and chroma-value or to a*, and b* value. Specifically, for the Dawn color, the chroma value should be larger than the hue value, while for Charcoal Solid, the tolerance for the b* value should be slightly greater than that for the a* value. In terms of lightness tolerance, it is asymmetric for the Dawn color. This means that the positive L* value can exhibit more variation than the negative L* value, indicating that Dawn is more sensitive to darker color differences than lighter ones. The lightness tolerance for Charcoal Solid is not symmetrical either, allowing slightly more difference in positive direction.

The new color tolerances are presented across three distinct customer satisfaction levels: 80%, 85%, and 90%. For a premium automotive company, it is recommended to adhere to the 90% satisfaction rate to maintain high customer satisfaction. The recommended tolerances corresponding to 90% customer satisfaction can be seen in Table 7. It is noteworthy that all updated tolerances are generally more allowing compared to VCC's existing standards. This indicates that customers are willing to accept a greater degree of color variation than what is currently allowed by VCC. However, one should keep in mind that the tolerances used by automotive companies should be stricter than the average buyer to ensure high customer satisfaction. The implementation of these new tolerance limits holds the potential to facilitate the utilization of more sustainable materials within the automotive industry. It is known that adhering to color tolerances becomes more challenging when working with sustainable materials, due to variations in material properties. Therefore, these new requirements offer a solution that promotes the adoption of sustainable materials in automotive manufacturing while ensuring a high level of customer satisfaction. By striking this balance, the automotive industry can embrace more sustainable practices without compromising customer expectations.

Table 7, The new color tolerance recommendations.

Tolerance Level Dawn	**L***	**C***	**H***
90% Acceptance	+ 0,8; - 0,5	+ - 0,3	+ 0,2; - 0,3
Tolerance Level Charcoal Solid	**L***	**a***	**b***
90% Acceptance	+0,7; - 0,6	+ - 0,25	+ 0,4; -0,3

7.2. Conclusions on design proposals regarding forgiving appearance

The following section presents the conclusions drawn regarding design proposals based on the comprehensive analysis of theoretical foundations and interviews with design and color experts.

- How can we design vehicle interiors in a way that allows a more forgiving combination of color variants?

The findings of the study indicate that a more forgiving appearance in vehicle interiors can be achieved by applying several different techniques. One example is to incorporate transition details between two different materials, which can make color differences between them more acceptable. Additionally, such details can serve as a visual focus, detracting attention from any color differences. Another design recommendation is to embrace greater color variation instead of uniformity, as this will also contribute to a more forgiving appearance. However, this should be done with caution as to not create an unharmonious appearance. Furthermore, materials that possess greater structural complexity can be more accommodating towards greater color tolerances. Lastly, careful consideration should be given to the selection of colors. This is largely because the eye's sensitivity to differences in hue depends on the color's placement in the color sphere. For example, differences in orange hues are easier to notice than differences in blue-green hues. In other words, choosing color wisely can help keep appearances uniform.

7.3. Future work and recommendations

As mentioned previously in this report, the plaques utilized in the study were arranged somewhat in a cross-shaped pattern when plotted in a graph, both for Dawn and Charcoal Solid. Although these plaques cover much of the area of interest, some potentially significant gaps do exist between the plaques. As the new recommendations are modeled based on the acceptance of these plaques, it is crucial to cover enough area for the analysis to be accurate. In order to achieve more precise results, more deviated plaques would have to be introduced in the study, covering more of the gaps between the already existing plaques. Also, in order to more effectively analyze and discern differences along each coordinate axis when utilizing the L*a*b* or L*C*H* color system, it could be advantageous to include more plaques in a plus-shaped pattern. This would enable a more straightforward and thorough examination of color tolerances for each individual axis. For the reasons stated above, it is recommended to expand this study by testing more deviated plaques in areas of interest for both Dawn and Charcoal Solid.

Furthermore, only two colors have been tested in this study, Dawn and Charcoal Solid. It is difficult to say for certain if the tolerance recommendations provided in the report would be appropriate for other colors as well. This is mainly because color theory claims that variances in hue are perceived with varying difficulty based on the color’s location in the color sphere. To develop appropriate tolerances for other colors, they should be tested in the same manner as this study has done.

8

REFERENCES

The present chapter is dedicated to the references used in the research project. This chapter provides a comprehensive list of all the sources cited throughout the thesis, including academic articles, books, reports, and other relevant materials.

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APPENDIX

Appendix 1 – Dawn plaques

Dawn plaques									
		Ordered value (SCI)			Measured value (SCI)				
	Name	**ΔL***	**ΔC***	**ΔH***	**ΔL***	**ΔC***	**ΔH***	**ΔE00**	**Gloss**
A	Master	0	0	0	0	0	0	0	4,27
B	D01	0	0,3	0,2	0	0,3	0,23	0,44	4,27
C	D02	0	0,3	-0,2	-0,03	0,31	-0,21	0,4	4,27
D	D03	0	-0,3	0,2	-0,03	-0,25	0,22	0,37	4,08
E	D04	0	-0,3	-0,2	-0,03	-0,28	-0,19	0,38	4,31
F	D05	0	0,45	0,3	-0,21	0,45	0,33	0,65	4,12
G	D06	0	0,45	0	-0,07	0,44	0	0,38	4,11
H	D07	0	0,45	-0,3	-0,04	0,48	-0,31	0,61	4,12
I	D08	0	-0,45	0,3	-0,12	-0,42	0,35	0,6	4,08
J	D09	0	-0,45	0	0	-0,32	0,04	0,28	4,31
K	D10	0	-0,45	-0,3	-0,03	-0,45	-0,24	0,54	4,31
L	D11	0	0	0,3	-0,02	0,01	0,35	0,5	4,28
M	D12	0	0	-0,3	-0,09	0,02	-0,31	0,46	4,07
N	D13	0	0,6	0,4	-0,23	0,59	0,4	0,8	4,05
O	D14	0	0,6	-0,4	-0,06	0,68	-0,43	0,85	4,11
P	D15	0	-0,6	0,4	-0,05	-0,54	0,44	0,75	4,11
Q	D16	0	-0,6	-0,4	-0,13	-0,55	-0,42	0,78	4,29
R	D17	0,5	0	0	0,42	-0,01	0,03	0,18	4,22
S	D18	-0,5	0	0	-0,63	0,06	-0,03	0,27	4,04
T	D19	0,7	0	0	0,65	0,03	0,01	0,26	4,22
U	D20	-0,7	0	0	-0,76	0,1	0,02	0,32	4,01
V	D21	0,9	0	0	0,8	0,03	0,02	0,33	4,24
W	D22	-0,9	0	0	-1,04	-0,01	0,03	0,43	4,07
X	Master	0	0	0	-0,02	-0,04	-0,01		

Appendix 2 – Charcoal Solid plaques

Charcoal Solid plaques									
		Ordered value (SCI)			Measured value (SCI)				
	Name	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔE00**	**Gloss**
A	Master	0	0	0	0	0	0	0	4,1
B	C01	0	0,2	0,2	-0,08	0,21	0,14	0,34	4,15
C	C02	0	-0,2	0,2	0,07	-0,23	0,23	0,41	4,21
~~D~~	~~C03~~	~~0~~	~~0,2~~	~~-0,2~~	~~-0,26~~	~~0,11~~	~~-0,02~~	~~0,19~~	~~4,27~~
E	C04	0	-0,2	-0,2	0,1	-0,18	-0,23	0,35	4,15
F	C05	0	0,3	0,3	-0,04	0,32	0,3	0,57	4,22
G	C06	0	0	0,3	0,11	-0,01	0,29	0,29	4,03
H	C07	0	-0,3	0,3	0	-0,26	0,33	0,51	4,03
I	C08	0	0,3	-0,3	0	0,35	-0,3	0,59	4,27
J	C09	0	0	-0,3	-0,08	-0,05	-0,25	0,25	4,07
K	C10	0	-0,3	-0,3	0,1	-0,22	-0,31	0,44	4,21
L	C11	0	0,3	0	0,01	0,23	0,12	0,37	4,14
M	C12	0	-0,3	0	0,11	-0,25	0,02	0,37	4,35
N	C13	0	0,45	0,45	0,05	0,43	0,45	0,78	3,96
O	C14	0	-0,45	0,45	0,08	-0,45	0,41	0,78	3,96
P	C15	0	0,45	-0,45	-0,12	0,42	-0,29	0,69	4,09
Q	C16	0	-0,45	-0,45	-0,02	-0,3	-0,42	0,59	4,25
R	C17	0	0,6	0,6	0,06	0,52	0,55	0,95	4,26
S	C18	0	-0,6	0,6	-0,04	-0,58	0,58	1,02	2,17
T	C19	0	0,6	-0,6	-0,11	0,47	-0,57	0,89	3,9
U	C21	0,5	0	0	0,54	-0,05	-0,02	0,22	3,97
V	C22	0,7	0	0	0,67	-0,04	0,06	0,26	4,12
W	C23	0,9	0	0	0,88	-0,02	0,14	0,36	4,16
X	C24	-0,5	0	0	-0,48	-0,05	-0,07	0,21	4,05
Y	C25	-0,7	0	0	-0,59	-0,03	-0,08	0,24	4
~~Z~~	~~C27~~	~~0~~	~~-0,2~~	~~-0,6~~	~~-0,08~~	~~-0,22~~	~~-0,56~~	~~0,62~~	~~4,18~~
Å	Master	0	0	0	0,05	0,01	0		

Appendix 3 – User test procedure

1. Ask participant to sign GDPR form
3. Write down information about the participant (gender, age, car/no car, vision impairment, blue-light blocking glasses, occupation)
4. Switch off overhead lights
5. Let participant perform X-rite Hue test at stationary computer
6. Switch on the overhead lights
7. Provide participant with information about the test (seated in the car):

   “This study is about the color of interior components, i.e., the parts that are visible in the car. Imagine that you are one of Volvo's customers who has just bought a new car. We will show you two plaques that you will judge based on their color. Imagine that these two plaques correspond to two components in your car that are placed next to each other. We now want you to decide if you can see any difference between the plaques or if you judge them to be the same, and if you deem the match as acceptable. It will not differ significantly between the plaques. Remember that there is no right or wrong, and that the answer "I see a difference" is not necessarily "better" than the answer "I don't see a difference". We are only interested in your opinion, and what you think about the interior of your car.”

8. Car test:
   1. Start with position 1, 2 then 3
   2. “Do you see any difference?” – Yes/No. If yes, why?
   3. “Do you think the match is okay or not okay?”

9. Go to light booth, turn on D65
11. Give participant white coat and adjust light booth height
13. Switch off overhead lights
14. Let the participant look into the light booth for 1 minute to adjust the eyes
15. Information about light booth test:

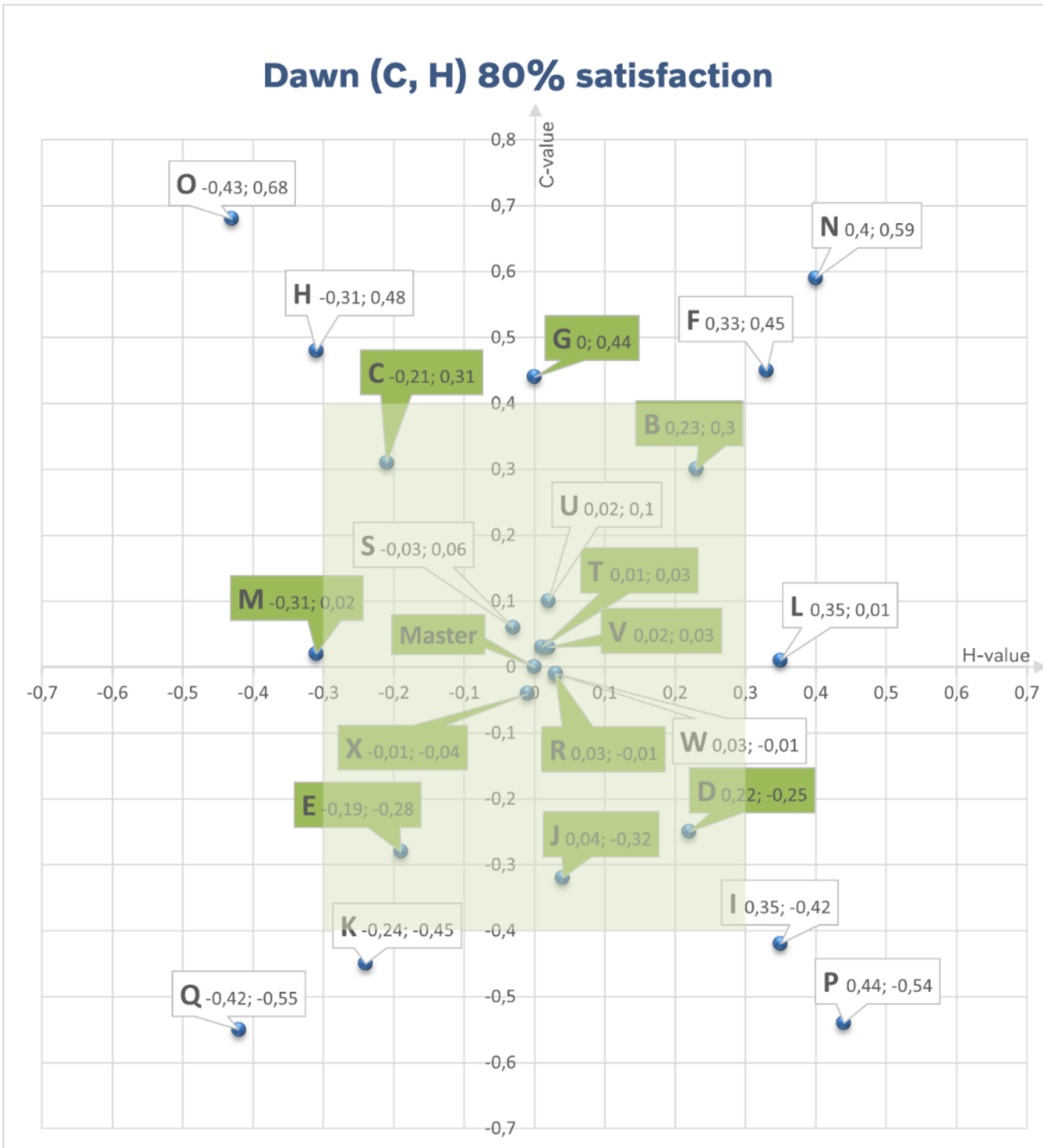
    “Now that you have understood the context, we want you to apply the same type of thinking and judge these plaques in a light booth. We will show you a number of different combinations and you will answer to the same questions as before. You will only get to look at each comparison for about 10 seconds, so we want you to make a rather quick decision. Not all plaques will have a difference and remember that we want you to answer from the perspective that you are a Volvo customer. You are allowed to look from different angles, but you cannot touch the plaques, and between the comparisons you can look away from the light booth to rest your eyes if needed”

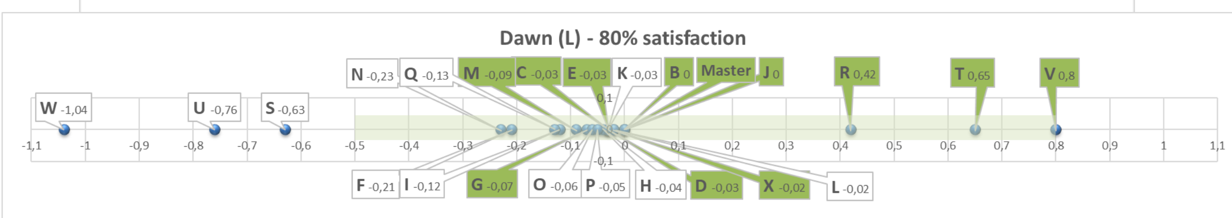
17. Start test

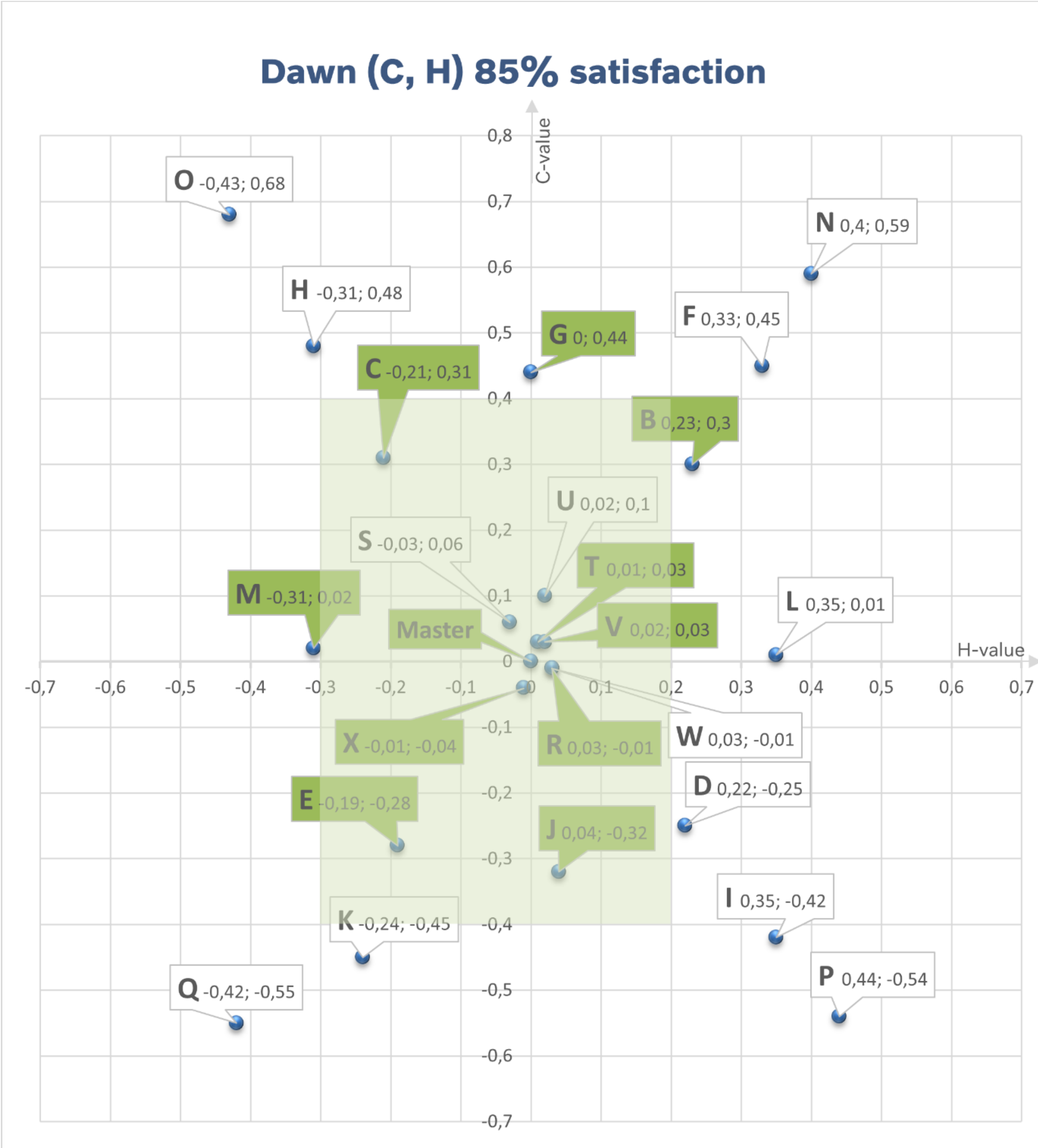
    a) Change combinations
    b) Ask questions
    c) Document answers

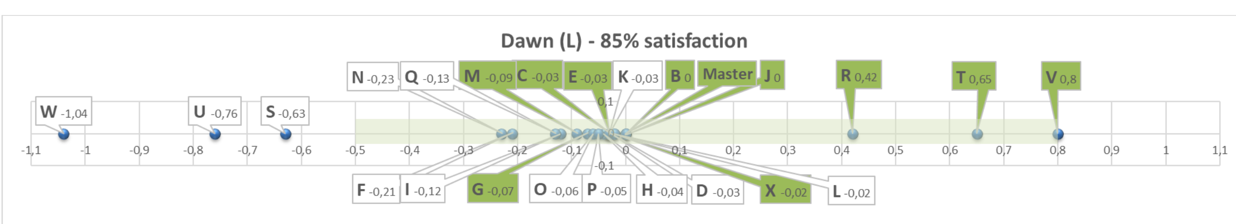
Appendix 4 – Scatter charts with tolerance limits

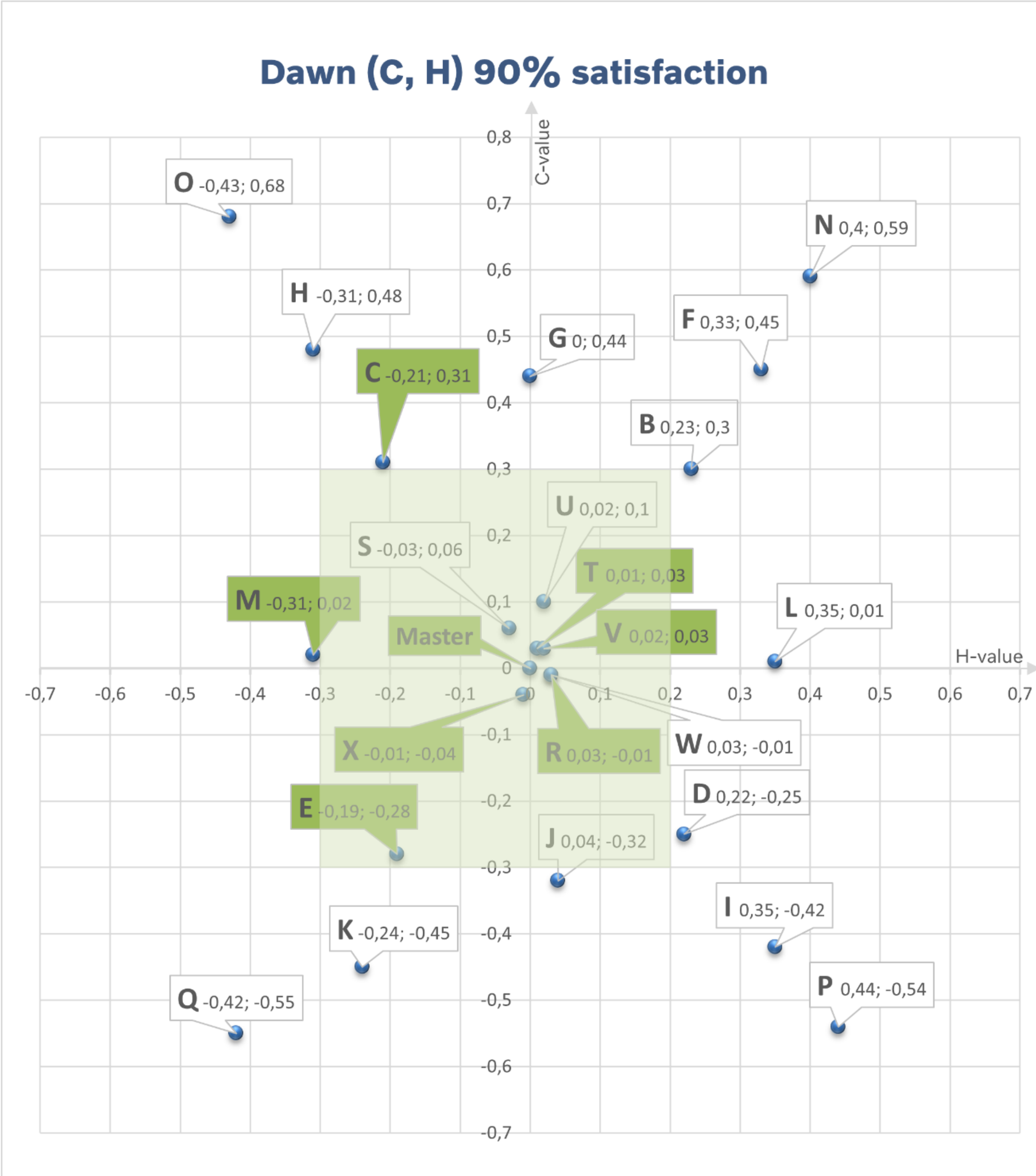
Below follow scatter charts that illustrates the new tolerances for the 3 different customer acceptance levels (80%, 85% and 90). The green labels represent plaques which have been rated acceptable by customers in the chosen interval. Furthermore, the green rectangles represent the new tolerance limits, and are based on an approximation of the acceptance ratings of the plaques. To ensure ease of implementation, the new tolerances were rounded to whole and half numbers with one decimal.

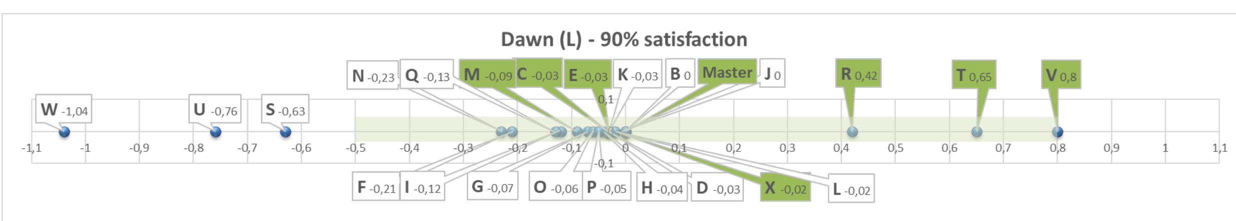


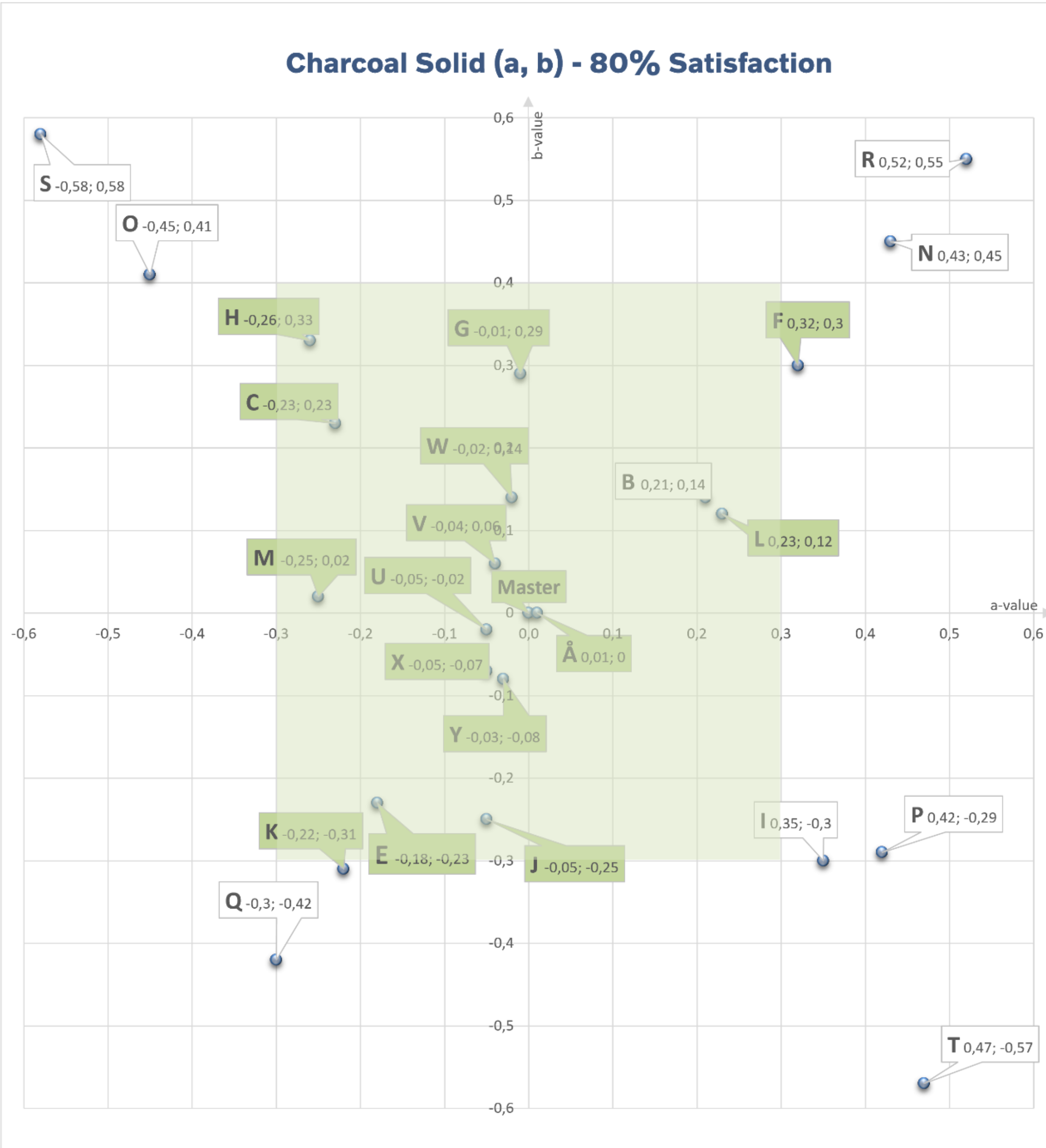


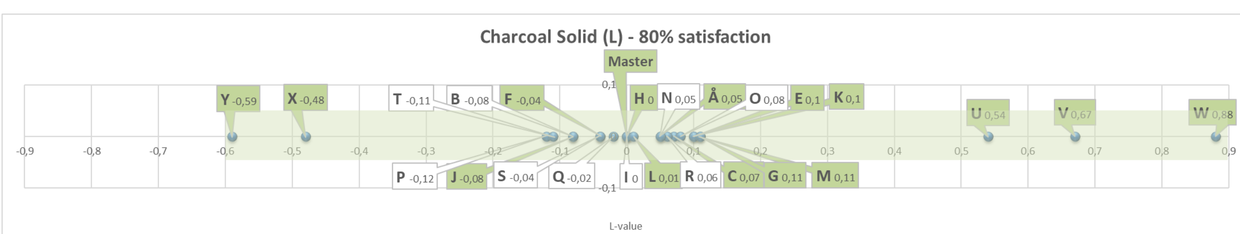

Dawn (C, H) 85% satisfaction
C-value
H-value
O -0,43; 0,68
N 0,4; 0,59
H -0,31; 0,48
F 0,33; 0,45
G 0; 0,44
C -0,21; 0,31
B 0,23; 0,3
U 0,02; 0,1
S -0,03; 0,06
T 0,01; 0,03
M -0,31; 0,02
V 0,02; 0,03
L 0,35; 0,01
Master
W 0,03; -0,01
X -0,01; -0,04
R 0,03; -0,01
D 0,22; -0,25
E -0,19; -0,28
J 0,04; -0,32
I 0,35; -0,42
K -0,24; -0,45
P 0,44; -0,54
Q -0,42; -0,55

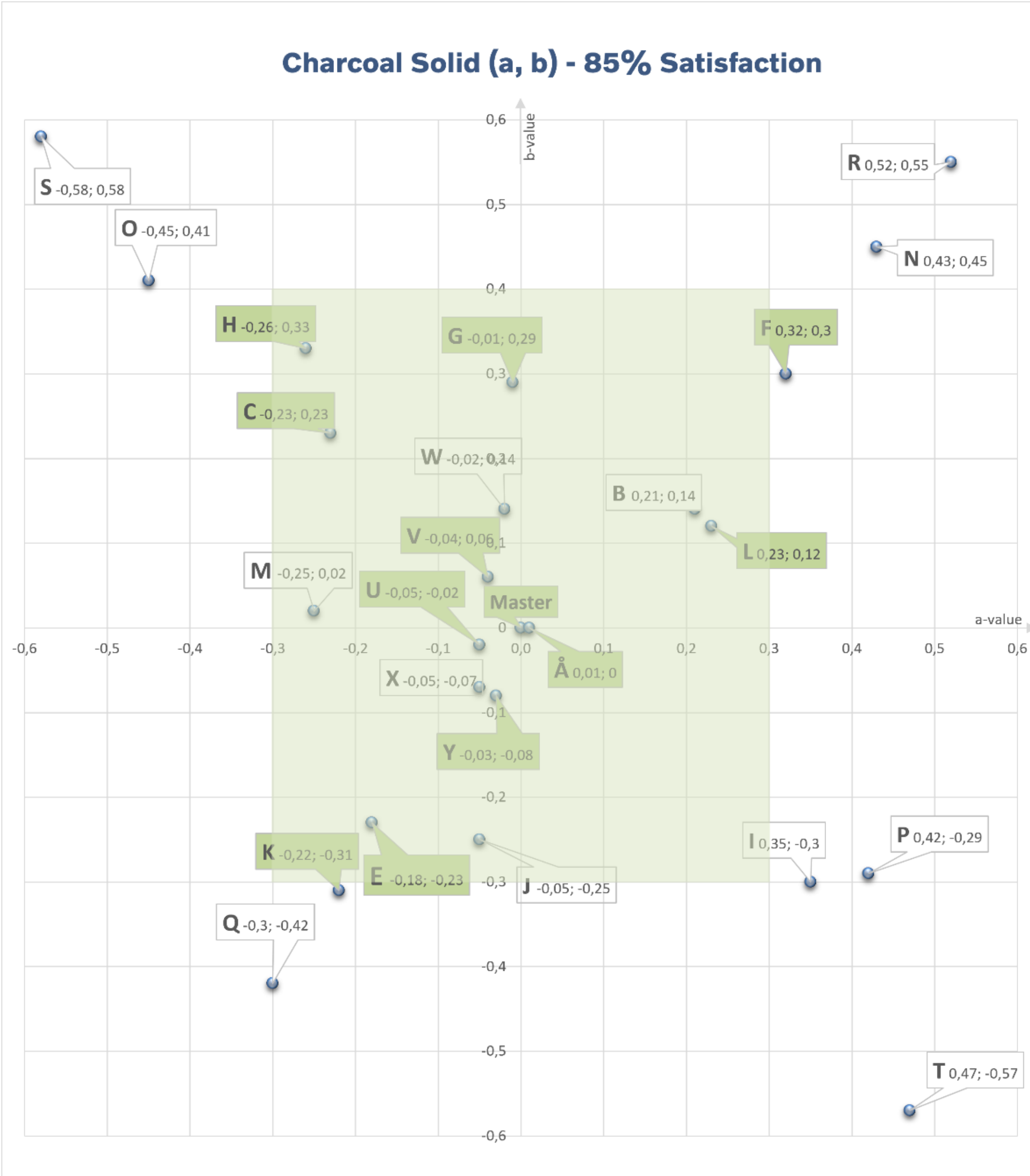

Dawn (L) - 85% satisfaction
W -1,04
U -0,76
S -0,63
N -0,23
Q -0,13
M -0,09
C -0,03
E -0,03
K -0,03
B 0
Master
J 0
R 0,42
T 0,65
V 0,8
F -0,21
I -0,12
G -0,07
O -0,06
P -0,05
H -0,04
D -0,03
X -0,02
L -0,02
L-value

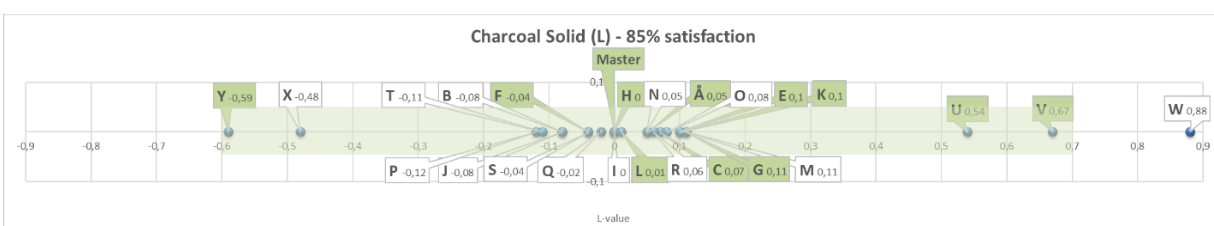

Dawn (C, H) 90% satisfaction
C-value
H-value
O -0,43; 0,68
N 0,4; 0,59
H -0,31; 0,48
F 0,33; 0,45
G 0; 0,44
C -0,21; 0,31
B 0,23; 0,3
U 0,02; 0,1
S -0,03; 0,06
T 0,01; 0,03
M -0,31; 0,02
V 0,02; 0,03
L 0,35; 0,01
Master
W 0,03; -0,01
X -0,01; -0,04
R 0,03; -0,01
D 0,22; -0,25
E -0,19; -0,28
J 0,04; -0,32
I 0,35; -0,42
K -0,24; -0,45
P 0,44; -0,54
Q -0,42; -0,55

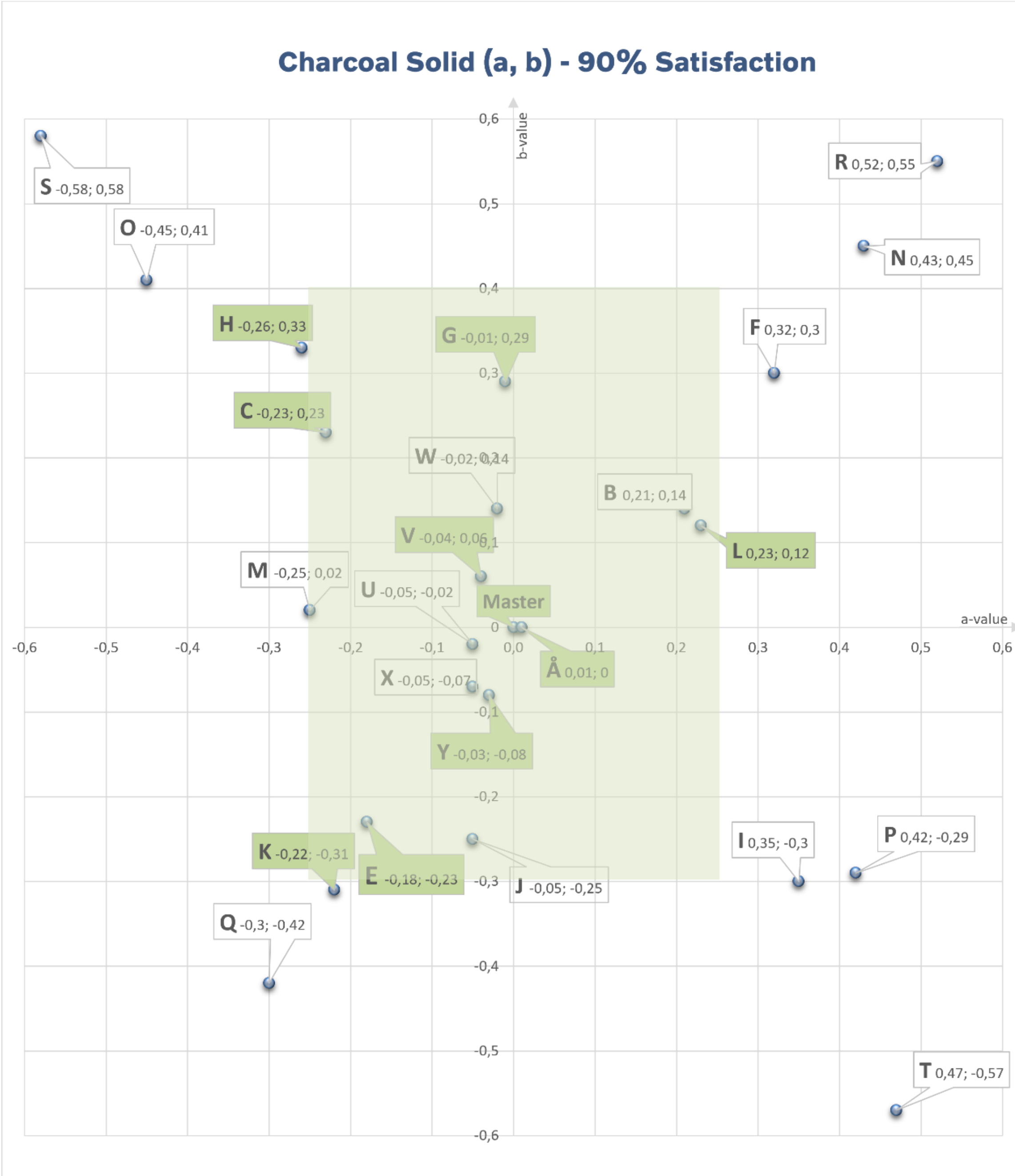

Dawn (L) - 90% satisfaction
W -1,04
U -0,76
S -0,63
N -0,23
Q -0,13
M -0,09
C -0,03
E -0,03
K -0,03
B 0
Master
J 0
R 0,42
T 0,65
V 0,8
F -0,21
I -0,12
G -0,07
O -0,06
P -0,05
H -0,04
D -0,03
X -0,02
L -0,02
L-value

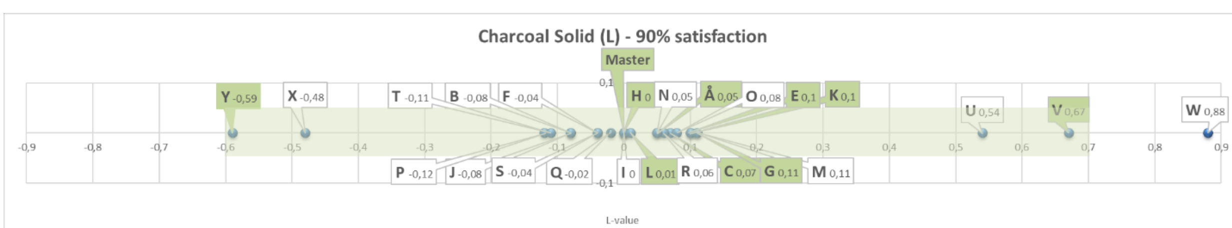

Charcoal Solid (a, b) - 80% Satisfaction
b-value
a-value
S -0,58; 0,58
O -0,45; 0,41
R 0,52; 0,55
N 0,43; 0,45
H -0,26; 0,33
G -0,01; 0,29
F 0,32; 0,3
C -0,23; 0,23
W -0,02; 0,14
B 0,21; 0,14
V -0,04; 0,06
L 0,23; 0,12
M -0,25; 0,02
U -0,05; -0,02
Master
Å 0,01; 0
X -0,05; -0,07
Y -0,03; -0,08
K -0,22; -0,31
E -0,18; -0,23
J -0,05; -0,25
I 0,35; -0,3
P 0,42; -0,29
Q -0,3; -0,42
T 0,47; -0,57


Charcoal Solid (L) - 80% satisfaction
Master
Y -0,59
X -0,48
T -0,11
B -0,08
F -0,04
H 0
N 0,05
Å 0,05
O 0,08
E 0,1
K 0,1
U 0,54
V 0,67
W 0,88
P -0,12
J -0,08
S -0,04
Q -0,02
I 0
L 0,01
R 0,06
C 0,07
G 0,11
M 0,11
L-value


Charcoal Solid (a, b) - 85% Satisfaction
b-value
a-value
S -0,58; 0,58
O -0,45; 0,41
R 0,52; 0,55
N 0,43; 0,45
H -0,26; 0,33
G -0,01; 0,29
F 0,32; 0,3
C -0,23; 0,23
W -0,02; 0,14
B 0,21; 0,14
L 0,23; 0,12
V -0,04; 0,06
M -0,25; 0,02
U -0,05; -0,02
Master
Å 0,01; 0
X -0,05; -0,07
Y -0,03; -0,08
K -0,22; -0,31
E -0,18; -0,23
J -0,05; -0,25
I 0,35; -0,3
P 0,42; -0,29
Q -0,3; -0,42
T 0,47; -0,57


Charcoal Solid (L) - 85% satisfaction
Master
Y -0,59
X -0,48
T -0,11
B -0,08
F -0,04
H 0
N 0,05
Å 0,05
O 0,08
E 0,1
K 0,1
U 0,54
V 0,67
W 0,88
P -0,12
J -0,08
S -0,04
Q -0,02
I 0
L 0,01
R 0,06
C 0,07
G 0,11
M 0,11
L-value


Charcoal Solid (a, b) - 90% Satisfaction
b-value
a-value
S -0,58; 0,58
O -0,45; 0,41
R 0,52; 0,55
N 0,43; 0,45
H -0,26; 0,33
G -0,01; 0,29
F 0,32; 0,3
C -0,23; 0,23
W -0,02; 0,14
B 0,21; 0,14
L 0,23; 0,12
V -0,04; 0,06
M -0,25; 0,02
U -0,05; -0,02
Master
Å 0,01; 0
X -0,05; -0,07
Y -0,03; -0,08
K -0,22; -0,31
E -0,18; -0,23
J -0,05; -0,25
I 0,35; -0,3
P 0,42; -0,29
Q -0,3; -0,42
T 0,47; -0,57


Charcoal Solid (L) - 90% satisfaction
Master
Y -0,59
X -0,48
T -0,11
B -0,08
F -0,04
H 0
N 0,05
Å 0,05
O 0,08
E 0,1
K 0,1
U 0,54
V 0,67
W 0,88
P -0,12
J -0,08
S -0,04
Q -0,02
I 0
L 0,01
R 0,06
C 0,07
G 0,11
M 0,11
L-value

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