Optical properties of hair and their role in precise coloring: application of the chromalens algorithm for color adaptation to different types of lighting

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Abstract. This article examines the modern understanding of the optical behavior of the hair fiber and its relevance for professional hair coloring, particularly under variable and multi-source lighting conditions. With the growing use of LED systems, studio lighting, and runway illumination, hair color has become increasingly unstable to the eye, even when the pigment formula itself is technically accurate. Based on current scientific evidence, the paper explains how the condition of the cuticle, the degree of porosity, pigment depth, and internal light scattering shape the final visual appearance of color. Special attention is given to the fact that hair is not an optically uniform structure: different micro-zones of the same strand may react differently to studio, natural, stage, and LED lighting, resulting in uneven tone perception.

In this context, the article positions the ChromaLens Precision Mapping methodology as an engineering-based approach to predictive coloring. ChromaLens Precision Mapping integrates optical diagnostics, photometric parameters, pigment-depth analysis, and formula adaptation for specific lighting scenarios. This makes it possible to minimize unwanted tonal shifts, increase color stability, and maintain three-dimensional visual depth even in motion. This is especially important for the fashion industry, runway shows, and professional photo shoots.

The paper also outlines key directions for future research, including more precise modeling of hair's micro-optical zones, the development of standardized predictive algorithms, and the creation of digital tools capable of accounting for the individual optical properties of the hair fiber. Overall, the presented material provides a scientific foundation for advancing color technologies and improving professional practice within the beauty and fashion domains.

Keywords: hair optics, diffuse scattering, coloristics, ChromaLens Precision Mapping, color stability.

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Introduction

In professional coloristics, the issue of hair color stability under different types of lighting is of key importance, since it is the interaction of light waves with the microstructure of the hair fiber that determines its visual appearance in real conditions (in the studio, on the catwalk, under LED panels, or in a natural environment) [1; 2]. Hair is not optically homogeneous. It has been shown that its cuticle, cortical layer, and internal porous structures refract, scatter, and reflect light in different ways. This forms a complex spectral profile that changes depending on the angle of observation, surface condition, and lighting intensity [3]. This is why the same color can look cooler in the studio, warmer under stage lighting, and neutral in daylight. This variability creates significant difficulties for colorists, as traditional techniques do not provide for optical analysis of hair and do not allow predicting color behavior in real conditions.

Modern research shows that an increase in hair porosity or damage to the cuticle layer significantly increases the proportion of diffuse scattering, weakens mirror reflection, and reduces color depth, which is especially noticeable under LED lighting and stage lighting [4; 5]. In such conditions, classic coloring methods (balayage, airtouch, foil techniques, slicing) do not take into account either the spectral characteristics of lighting or the physical properties of hair, which leads to tone instability, loss of three-dimensionality, and shade defects that only become apparent after the client leaves the salon.

This creates a need for technology that can not only analyze the microstructural and biometric properties of hair, but also take into account optical laws, spectral behavior of pigment, reflection intensity, and the nature of light scattering in each microzone of the hair. ChromaLens Precision Mapping (CLPM) is just such a tool, and it's a pretty innovative technique. CLPM combines optical analysis, photometric modeling, and microzone color adaptation to ensure shade accuracy regardless of lighting type, angle, and dynamic shooting conditions.

Literature Review

The modern hair coloring industry is rapidly shifting towards high visual accuracy and photometric stability of results. Hair color should look equally convincing in daylight, under studio softboxes, LED panels, on the catwalk, in the dressing room, and on social media. However, lighting remains one of the least controllable factors in the practice of hair colorists. Studies by M. Holmes [1] and A. Hamdoh [2] prove that the perception of hair color varies significantly depending on the spectral composition of light, its intensity, and direction. The same dyed strand can appear deeper, lighter, or with a different shade shift under different lighting conditions. This creates a critical problem for premium colorists, where not only a beautiful color “here and now” is expected, but also its predictable behavior in a dynamic visual environment.

At the same time, the amount of data on the complex optical properties of hair fiber is growing. In their works, A. Hamdoh [2] and F. Lona-Durazo [3] indicate that hair functions as a translucent cylindrical biopolymer with a multi-level structure, combining refraction, scattering, specular and diffuse reflection, polarization effects, and internal absorption caused by pigment and keratin structure. Authors E. Martins [4], T. K.eelima [5], S. K. Pal [6] have shown that cuticle damage, changes in porosity, and loss of lipids and melanin due to lightening or repeated coloring procedures not only worsen the mechanical properties of hair, but also radically change its optical response: gloss is reduced, diffuse scattering is enhanced, and unwanted dullness or “dusty” shades appear. For a specialist, this means that even a perfectly calculated basic color formula does not guarantee the predicted visual result without taking into account the optical condition of the hair and the type of lighting.

Despite the accumulation of data by S. K. Pal [6], L. Heng [7], and K. Keis [8] on the structure of damage and the optical behavior of hair, empirical approaches that focus on the "eye of the master" rather than measurable parameters still dominate professional practice. Visual assessment of color under one type of lighting does not allow predicting its appearance in studio, catwalk, or stage conditions, which is especially problematic for the fashion segment, photo shoots, and brand collaborations, where hair is expected to have a stable three-dimensional color and controlled shine in the camera lens. In these conditions, there is a need for integrated algorithms that simultaneously take into account the microstructure and degree of hair damage, the depth and distribution of pigment, the nature of light scattering in the hair fiber, and the specifics of different types of lighting.

The aim of the study is to scientifically substantiate the optical mechanisms that determine hair color behavior under different types of lighting and to analyze the application of the ChromaLens Precision Mapping (CLPM) system for adapting coloring to studio, natural, stage, and LED lighting modes.

Research Results

Over the past decade, the optical properties of hair fiber have gradually moved from purely empirical observations to systematic scientific research. Whereas previously the results of coloring were mainly explained by the selection of pigment formulas and application techniques, today it is becoming clear that the final perception of color is determined by a complex of photometric, structural-biophysical, and spectral parameters [1; 2; 9]. In this context, coloristics ceases to be exclusively an "applied art" and is increasingly positioned as an optically controlled technology that is sensitive to fiber microstructure and lighting characteristics.

Numerous publications in dermatology, biophysics, and cosmetic science indicate that the visual perception of hair color is the result of a combination of specular and diffuse reflection, internal scattering, refraction, and absorption of light within the fiber volume [1; 3; 8; 10]. Each of these mechanisms is determined by the condition of the cuticle, the level of porosity, the content and spatial distribution of melanin, as well as the overall structural integrity of the hair shaft. Hair color is not a fixed parameter, but rather the result of the dynamic interaction between light flow and biopolymer structure [11; 12].

For the fashion industry, where hair color is an integral part of the visual composition of an image, this optical sensitivity is of particular importance. During shows, photo shoots, and video shoots, hair is constantly exposed to changing lighting scenarios, from cold studio panels to warm catwalk spotlights and LED structures. In these conditions, classic coloring techniques, which are based mainly on macro-visual assessment and the experience of the master, are insufficient to ensure shade stability. That is why there is a need to create engineering systems capable of taking into account the optical heterogeneity of the hair and predicting color behavior under different types of lighting.

Against this backdrop, the ChromaLens Precision Mapping technique can be seen as an attempt to integrate modern ideas about hair fiber optics into professional colorist practice. The proprietary ChromaLens Precision Mapping system, originally developed as a microzonal technology for hair diagnosis and coloring, opens up the possibility of forming just such an optics-oriented approach. Its multi-level structure includes optical diagnostics, biometrics, trichological assessment, facial morphology, natural color code analysis, behavioral coloristics, and a photometric unit that simulates the appearance of color under different lighting conditions.

According to modern theoretical models, hair fiber is a complex optically heterogeneous system that combines the properties of a translucent biopolymer, a multilayer microlens structure, and a medium with pronounced internal scattering [1; 8; 11; 13]. When light falls on the surface of the hair, several parallel processes occur:

part of the light is reflected from the surface of the cuticle according to the law of mirror reflection;

part is refracted, penetrating through the cuticle and passing to the cortical layer;

in the inner layers, multiple acts of scattering and absorption occur, caused by microstructural inhomogeneities and the presence of pigment granules;

the modified light flux is partially returned to the outside in the form of diffuse reflection with a different spectral profile.

It is the ratio of the specular and diffuse components, as well as the depth of internal absorption, that determine the visual impression of color, its brightness, saturation, depth, the effect of "internal glow" and three-dimensionality.

The cuticle, represented by overlapping scales, acts as a primary optical filter and gloss modulator. Its smoothness, integrity, scale angle, and surface condition determine the nature of surface reflection. It has been shown that an intact, tightly closed cuticle ensures the dominance of the mirror component, forming a pronounced, localized shine, especially noticeable under highly directional studio light sources [2]. In contrast, a damaged, raised, or eroded cuticle increases the proportion of diffuse scattering, which manifests itself in dullness, blurred reflections, and loss of clarity of the contours of the reflections. It is important to emphasize that the degree of cuticle openness directly correlates with optical color instability under LED and stage lighting conditions [3; 13]. This means that two hairs with the same pigment formula but different cuticle conditions can exhibit significantly different visual characteristics.

The cortical layer acts as the internal optical system of the fiber. It contains melanin granules, which determine the natural pigment background and form the spectral absorption profile [4; 8]. The degree and nature of light interaction with the pigment matrix determine parameters such as: color depth; shade stability when the angle of illumination changes; the presence or absence of the "3D glow" effect; sensitivity to warm or cold spectral ranges.

Recent studies emphasize that it is the spatial distribution of pigment (surface, mid-layer, or deep) that largely determines the three-dimensionality of color and its photostability [11; 12]. Surface coloring, which is mainly focused on the upper layers of the cortical layer, is prone to "cutting" by studio lighting, creating a visually flat, less saturated tone. In contrast, multi-layer pigmentation with sufficient depth provides multiple internal absorption and re-reflection, forming an internal glow effect.

The porosity of the fiber, the presence of microcavities, and disturbances in the water-lipid balance significantly alter the distribution of light within the hair. As porosity increases, the proportion of diffuse scattering increases, leading to a decrease in overall brightness and shine, loss of sharpness of shadows and reflections, the appearance of uncontrolled warm or "dirty" shades under warm spotlights, and increased cold reflections under LED sources [5; 6]. These effects are especially significant for damaged, lightened, or chemically treated hair, which is a typical object of work in the fashion industry.

Recent studies have shown that hair color is not invariant with respect to the type of lighting (Table 1). On the contrary, the spectral composition of the light source, its directionality, and intensity significantly modify the final perception of the shade [6; 7; 9; 10]. For professional colorists, this means that color assessment in one lighting situation does not guarantee its similar perception in another.

Table 1

Optical characteristics of hair under different types of lighting

Type of lighting	Spectral characteristics	Effect on surface gloss	Effect on pigment depth	Typical shade shifts
Studio	Cold spectrum dominates, narrow directionality	Enhances mirror reflection	Reduces visible depth	Shift to cold tones, intensification of "glare"
Natural day	Uniform spectral distribution	Balance between surface and interior	Maximum stability	Most realistic color reproduction
Stage/catwalk	Warm peaks + LED dominant	Breaks up glare, enhances diffusion	May "eat away" at cold components	Warmer, more intense, less stable tone
LED panels	Cold or mixed spectral profile	Enhances surface defects	Emphasizes depth inconsistencies	Shift to cool shades, increased contrast

Source: compiled by the author based on [7; 8; 9; 10]

Studio light sources are typically characterized by high directionality and a significant proportion of the cold spectrum. This leads to a sharp increase in mirror reflection from intact areas of the cuticle and a simultaneous decrease in visual color depth [7]. As a result, shades appear lighter and colder, the upper pigment layer is activated more strongly than deeper structures, and the three-dimensional effect is partially lost, especially with surface coloring. This phenomenon is well known in beauty photography, where colors that appear soft and balanced in natural light often look "cooler" and more contrasting in the studio.

Unlike studio light sources, natural daylight has a broad and relatively uniform spectral coverage. Biophysical studies show that it is diffused daylight that most accurately reflects the real spectral profile of hair, as it evenly activates the surface and deep pigment layers [8]. At the same time, natural lighting acts as a "reference standard" against which it is advisable to calibrate all other scenarios.

For the author's CLPM algorithm, natural light is used as a basic photometric calibrator. Specifically, during the diagnostic process, the stability of the pigment during the transition from artificial to daylight is assessed, and areas where significant shade shifts are possible are identified.

Stage lighting is characterized by a combination of warm spectral peaks (yellow-orange-red range) and intense LED arrays, often with dynamically changing scenarios [9; 10]. In such an environment, copper and gold components of the shade are significantly enhanced, while cool tones may appear "dirty" or less pronounced. Meanwhile, areas with increased porosity demonstrate excessive scattering, leading to a loss of structural color clarity.

Catwalk lighting is the toughest test for color fastness. Models are in motion, the angle of incidence and intensity of light change every second, and the camera captures not only static color but also the dynamics of its changes. Under these conditions, traditional formulas often "break down," while optically adapted schemes, such as CLPM, demonstrate significantly higher stability.

One of the fundamental principles of modern hair optics is the recognition that the hair canvas cannot be considered an optically homogeneous structure [6; 8]. Even within a single strand, there are areas with different porosity, varying density and cuticle openness, different melanin concentrations, different water-lipid saturation, areas of previous lightening or chemical treatment. This segmentality creates a situation in which the same light flux is absorbed, scattered, and reflected differently in neighboring microzones. In practice, this manifests itself in uneven tone, local "drops" in depth, and excessive reflections in certain areas.

This is where the conceptual difference of CLPM manifests itself: instead of the initial assumption of the relative homogeneity of the canvas, the technique is based on the postulate of its optical microzonality. Each microzone is considered as a separate optical object with its own set of parameters: surface reflection coefficient, degree of diffuse scattering, optical permeability, pigmentation depth, and reaction to different spectral ranges.

Based on the results of such diagnostics, an individual light scattering map is formed, on the basis of which microzonal formulas are constructed. This allows not only to "mask" problem areas, but also to purposefully use the strengths of individual zones (for example, areas with deep pigmentation to form optical support for the 3D effect).

One of the key factors that distinguishes premium coloring techniques from mass ones is the conscious construction of pigment depth. From a scientific point of view, pigment depth determines the length of the optical path of light in the fiber volume, the number of internal absorption acts, the frequency and "route" of repeated reflections, and the intensity of interference effects in a multilayer structure.

Modern research emphasizes that it is the interaction of light with the pigments of the cortical layer that provides the phenomenon of 3D visuality, when the color demonstrates a change in depth and saturation depending on the angle of incidence of light and the viewing angle [11; 12]. With insufficient pigmentation depth, studio and catwalk lighting "cuts off" the upper layers of color, forming a visually flat, "poster-like" shade. With sufficient depth, on the contrary, light is refracted and absorbed multiple times at different levels, creating a 3D glow effect. CLPM directly integrates these concepts by considering pigment depth as a quantitatively measurable optical parameter. Within the framework of microzonal analysis, the optical permeability (the ability of light to penetrate the thickness of the fiber), spectral absorption (preferred absorption ranges), and local response to studio, natural, stage, and LED lighting are evaluated for each zone.

The data obtained allows us to construct a pigment depth map and set a formula for each microzone that is adapted to its optical behavior. Experimental work shows that areas with deeply located pigment demonstrate higher stability under multi-point lighting and better preserve color uniformity in motion [10].

The further development of optical hair models logically leads to the use of photometry, a quantitative description of the interaction of light waves with material. A number of studies show that the photometric characteristics of hair can change significantly even within a day under the influence of humidity, changes in the angle of sunlight, temperature, and the spectrum of artificial light sources [1; 8]. No traditional coloring technique integrates these dynamic factors into its logic.

CLPM, on the contrary, is designed as a prediction system in which the angle of incident light, the intensity of diffuse scattering, the refractive properties of the cuticle, the dynamics of shadows and reflections, and the depth of pigmentation are considered as variable models rather than an unchanging "background." This allows the probability of color shift in each microzone to be assessed under various scenarios, including model movement, camera angle changes, and transitions between locations (backstage – catwalk – photo shoot). In fact, CLPM provides what can be defined as "visual stability in a multi-point lighting environment," where color retains its three-dimensionality, saturation, and relative tonal consistency despite aggressive lighting changes (Table 2).

Table 2

Comparison of ChromaLens Precision Mapping with traditional techniques

Parameter	Traditional techniques	CLPM
Light scattering	Ignored	Measured for each microzone
Specular/diffuse reflection	Not analyzed	Analyzed as a key factor in gloss and tone
Reaction to studio light	Unpredictable	Predictable through surface reflection models
Reaction to natural light	Varies randomly	Used as an optical calibration stage
Reaction to stage lighting	Uncontrollable	Modelled with warm spectral peaks
Pigment depth	Assessed visually	Measured and linked to 3D models
Three-dimensionality of color	Random	Predicted by photometric models
Stability in motion	Low	High
Use in fashion	Limited	Optimized for the catwalk and backstage

Source: compiled by the author

The author's color adaptation algorithm in CLPM can be described as a multi-stage system based on the sequential integration of optical, photometric, and structural-biophysical parameters.

Optical diagnostics. The reaction of hair to different spectral ranges is recorded, surface and internal reflection are measured, and the basic tendency for shade shifts to the cold or warm zone is assessed.

Assessment of scattering and porosity. Microzones with increased diffuse scattering, disturbed water-lipid balance, and unstable shine are identified. Compensatory corrections are immediately applied to them.

Calculation of pigment depth. The potential for 3D visualization and color photostability is assessed, and a pigment depth map is formed.

Formulation of microzone formulas. A formula is created for each microzone, taking into account the condition of the cuticle, degree of porosity, pigment depth, and target lighting scenarios (studio, catwalk, natural, mixed).

Photometric modeling of color behavior. It is predicted how the color will appear in motion, when changing the angle and intensity of light. If necessary, the formula is further adjusted.

Thus, analysis of current scientific data allows us to conclude that the optical behavior of hair is determined by a combination of structural (condition of the cuticle, porosity, pigment depth) and photometric (scattering, reflection, absorption) parameters. Hair color is a dynamic characteristic that is sensitive to the type of lighting, the angle of light incidence, the condition of the hair, and the spectral composition of the light sources. Modern traditional coloring techniques that do not take into account microzonal optical heterogeneity are unable to ensure color stability in the conditions of multi-point and variable lighting characteristic of the fashion industry. Meanwhile, the author's ChromaLens Precision Mapping algorithm offers a new coloring paradigm in which hair color is considered as the result of the controlled interaction of light and hair fiber, rather than just the sum of the pigment formula.

In this context, CLPM appears not just as another dyeing technique, but as an engineering system for color prediction and stabilization based on the principles of optics, structural biophysics, and photometry. It is precisely this integration of scientific knowledge with the practice of professional coloristics that gives reason to consider CLPM as a promising tool for the premium industry, capable of ensuring high accuracy, reproducibility, and optical color fidelity in the most complex lighting scenarios.

Conclusions

An analysis of the optical properties of hair and their effect on color stability under different types of lighting has shown that the light environment is one of the key factors determining the visual result of coloring. Hair fiber functions as a complex optical system, where the interaction of specular and diffuse reflection, internal scattering, absorption, and refraction forms a spectral profile that varies depending on the hair structure and lighting spectrum. That is why traditional coloring techniques that do not take into account the light behavior of hair often lead to tone instability, loss of three-dimensionality, or the appearance of unwanted shade shifts in studio, catwalk, or LED environments.

The CLPM method is distinguished by a systematic approach that integrates microzonal optical analysis, photometric modeling, and pigment depth assessment. As a result, CLPM ensures predictable color behavior in various lighting scenarios, including studio, natural, and stage lighting. Crucially, CLPM takes into account the response of each microzone to spectral peaks, refractive depth, and optical transmittance, enabling the creation of stable three-dimensional shades that do not “break” when the environment changes.

The results of the study show that CLPM is a highly effective technique for the fashion industry, where the requirements for photometric color accuracy are extremely high. In the context of Fashion Week, studio shoots, and runway shows, CLPM ensures shade stability, depth, shine, and color uniformity in motion—properties that are unattainable with classic techniques.

Prospects for further research

Further research is needed to better understand how different areas of hair interact differently with light. More accurate models need to be created that predict how color will look under different types of lighting.

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