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Modeling color transformations in augmented reality applications using multidimensional linear regression

ABSTRACT

Recent years have seen rapid adoption of augmented reality (AR) in e-commerce, enabling consumers to visualize products such as clothing, furniture, and cosmetics within real-world contexts using smartphones. While AR improves engagement and reduces return rates, accurate color reproduction remains a critical challenge affecting consumer trust and purchase decisions. Color distortions arise from smartphone display technologies, ambient lighting conditions, and viewing geometry. This study investigates color perception distortions in mobile AR and proposes a multivariate linear regression model to predict and compensate for color shifts. Device-displayed colors defined in CIE Lab space were mapped to visually perceived colors using empirical data obtained from controlled user experiments with standardized Pantone color references. The proposed model achieved an average color difference of ΔE = 3.17, which lies within commonly accepted industry tolerances, though it remains insufficient for high-precision color-critical applications. Additionally, ergonomic factors such as user posture and smartphone orientation were examined to minimize viewing-angle-induced color distortions. The results demonstrate that simple, interpretable regression models can improve AR color fidelity when combined with ergonomic optimization, while also highlighting the need for larger datasets and more advanced modeling approaches for commercial-grade deployment.

KEY WORDS
augmented reality, color perception, multivariate linear regression, smartphone displays, color calibration in AR

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Introduction

The COVID-19 pandemic accelerated the shift to online shopping, pushing consumers to seek remote ways to browse and buy products. Augmented reality (AR) emerged as a key tool, enabling users to virtually try on clothes, preview furniture, or test cosmetics – bridging the gap between online and in-store experiences.

Augmented reality has allowed buyers to lower the barrier between online and offline shopping, making the choice of goods convenient and more confident. As users grew accustomed to these benefits, companies continued to invest in AR innovation. (Wedel, Bigné & Zhang, 2020; Negm, 2025; Fritz, Hadi & Stephen, 2023).

A key feature of AR is its ability to blend real-time camera images with preloaded virtual objects. Accurate color rendering is essential for realism – color distortions from angle changes break immersion and make virtual elements appear unnatural. (Morimoto et al., 2017; Gegenfurtner, Weiss & Bloj, 2024; Finken et al., 2025). This is especially noticeable when the user constantly moves smartphone changing the angle of view. This phenomenon is explained by the main technologies of modern smartphones: OLED (Organic Light-Emitting Diode) and LCDs (Liquid-Crystal Displays). In 2025, OLED smartphone display shipments are expected to exceed 1 billion units. Apple plans to switch to OLED displays in all iPhone models starting in 2025, ditching LCD (Reuters, 2024; StartUs Insights, 2025).

Color distortions in such screens occur because when viewed at an angle, light from pixels passes through more display layers and changes direction. The best OLED screens have nearly perfect viewing angles, though a slight change can still be seen (StartUs Insights, 2025; Luo, 2016).

Thus, the problem of inaccurate color reproduction in augmented reality applications has real causes, and it can lead not only to lower user interest in viewing content, but also to financial losses if the application is part of an online sales system where color is important for consumers.

This paper solves the problem of modeling the transformation of color stimuli observed on smartphone screen as elements of an augmented reality application.

Related works

Research into improving color accuracy in augmented reality applications has been ongoing for many years (Abbasi et al., 2024; Wu et al., 2021; Zhang, Murdoch & Bachy, 2021; Kim et al., 2016; van Krevelen & Poelman, 2010). The importance of this problem, its impact on sales through augmented reality applications, and possible distortions in how visualized data is perceived in fields like medicine or education have led many researchers to study different ways to solve it. Murdoch (2023) evaluated the applicability of the CAM16 color perception model in an AR environment using an optical simulator. Objective measurements were taken using an AR optical simulator, and a psychophysical experiment on color matching was carried out for different foreground and background combinations. Color perception in AR was compared with that on a regular screen. One of the tasks where color perception of augmented reality content is extremely important – visual assessment of pH using test strips – is considered by Lee, Zhan & Wu (2019). They propose a smartphone-based solution that combines a dedicated color chart and a new color correction algorithm. The algorithm uses a spatially varying first-order regression model to accurately correct color based on both absolute luminance and scale.

To study differences in spectral sensitivity among observers, Zhai & Chen (2021) used a viewing box with neutral lighting conditions and participants compare the visible colors of eight base sets. This approach, where a specially designed mixed reality application with sample test colors is used and participants view the augmented reality content under controlled viewing conditions, was also applied by Zhang et al. (2023). In this research virtual reality technology was used to create realistic environments that could be changed in real time. Participants chose the object that most closely resembled a pre-determined achromatic standard.

Gil Rodríguez et al. (2024) describes a controlled metameric matching experiment using daylight reproduction and different display technologies. The study examines how the background correlated color temperature (CCT) affects color perception in AR. The experiment performs color matching between an AR RGB prototype and a reproduction of the daylight spectrum. The experiment examined different background CCTs and luminance levels.

Diaz-Barrancas et al. (2023) presented an AI-based chromatic aberration adjustment system based on a modified U-Net architecture designed for real-time applications in VR/AR. The system adapts to changing lighting conditions in real time. It overcomes the limits of traditional methods like histogram equalization and gamma correction, which do not handle fast lighting changes well.

It can be concluded that much attention is given to the practical aspects of color perception. Researchers develop prototypes, run user experiments, and record changes in color perception under different lighting conditions, display types, backgrounds, and display settings.

Despite many experimental studies, there's a lack of theoretical models that systematically explain color distortions in AR. Color perception in AR is influenced by factors like display transparency, chromatic adaptation, psychological context, and scene layout – making it difficult to formalize and insufficiently studied. Most models also assume fixed lighting and viewing, limiting their use in dynamic AR environments. To advance AR, we need formal models tailored to its specific conditions to enhance system calibration and color accuracy.

To address this, we propose using multivariate linear regression, which examines how multiple independent variables affect a dependent outcome. While newer methods like neural networks and decision trees exist, many still build on linear regression. Its main advantage is interpretability – models are transparent, easy to visualize, and widely applicable – making linear regression a reliable and practical approach even today (Montgomery, Peck & Vining, 2021).

In studying the features of color display in mixed reality technologies, regression analysis methods are also used: in the papers (Kim et al., 2016) the nonlinear nature of color distortion is represented using localized regression methods. Secondly, the distortion is modeled in the CIE XYZ color space, a device-independent format, based on empirical color measurements.

This paper proposes to build and train a multivariate linear regression model that will describe the color transformation of images displayed by augmented reality applications. The predictor and response variables are proposed to be coordinates of the device-independent color space.

Visual assessment of colors perceived by users is proposed to be carried out using specially developed test image objects that will be included in the augmented reality application and shown to the experiment participants under standardized daylight conditions provided by a viewing box.

Methodology

Studying the characteristics of color perception in augmented reality (AR) applications goes through several sequential stages. The main goal of such research is to understand how users perceive the colors of virtual objects superimposed on the real world and what factors can cause distortions.

The first stage involves developing the AR application itself. Due to the specifics of display technologies colors on a smartphone screen can appear different depending on the viewing angle. This is important in augmented reality applications, as the user constantly moves the smartphone to view virtual objects from different angles.

Therefore, the next stage of research is to determine typical user positions while interacting with an AR application. To achieve this, specialized experimental studies are conducted. During these experiments, user posture, head position, and the tilt and orientation of the smartphone are recorded.

The third stage involves developing the special test objects. These are typically color charts with pre-defined color values. Test charts are integrated directly into the augmented reality app. Users view them on the device screen, select the closest from the color standard patches and researchers evaluate how accurately the colors are displayed. The results are recorded and analyzed. Mathematical models can then be built using this data to describe how color distortions occur.

Multidimension linear regression is often used for this purpose. It could describe connection between colors in AR application and on-screen visible colors. This creates a model that predicts distortions and, if necessary, corrects the displayed colors. In general, the linear regression model can be written as

$$h(x) = a + b_1 x_1 + \ldots + b_d x_d = a + b \cdot x \quad (1)$$

where $x=(x_1,x_2,\ldots,x_d)$ – vector of input values – chart color coordinates in AR content, $b=(b_1,b_2,\ldots,b_d)$ – vector of model coefficients, a – free member. The main task in constructing such a model with optimal values of the coefficients b. They must ensure the minimization of a certain approximation quality criterion, Q.

In general, this requirement is written as the solution to an optimization problem:

$$b\ ^* = Q\ (b, x) \quad (2)$$

In this paper as criterion the sum of squared errors is adopted. $Q(b,x) = \sum_{i=1}^{d} \left(h\left(x_i, b\right) - y_i\right)^2$

The $y=(y_1,y_2,\ldots,y_d)$ – the desired response vector of color coordinates of on-screen visible colors.

When input data are represented as sets of vectors $X=(x_1,x_2,\ldots,x_n)^T$ and $Y=(y_1,y_2,\ldots,y_n)^T$ accordingly, a generalized multivariate linear model is used. In this case, the data are conveniently written as matrices:

$$Y_{n\times d} = X_{n\times(p+1)} B_{(p+1)\times d} \quad (3)$$

The input matrix $X_{n\times p+1}$ contains three coordinates for each of n chart color patches in AR content; the output matrix $Y_{n\times d}$ contains the corresponding output values – three coordinates of n on-screen visible colors. The model selects a coefficient matrix B^* that minimizes the root-mean-square error between the predicted and visible color values:

$$B\ ^* = argmin\, Q(B) = argmin \left\| H(X, B) - Y \right\|^2. \quad (4)$$

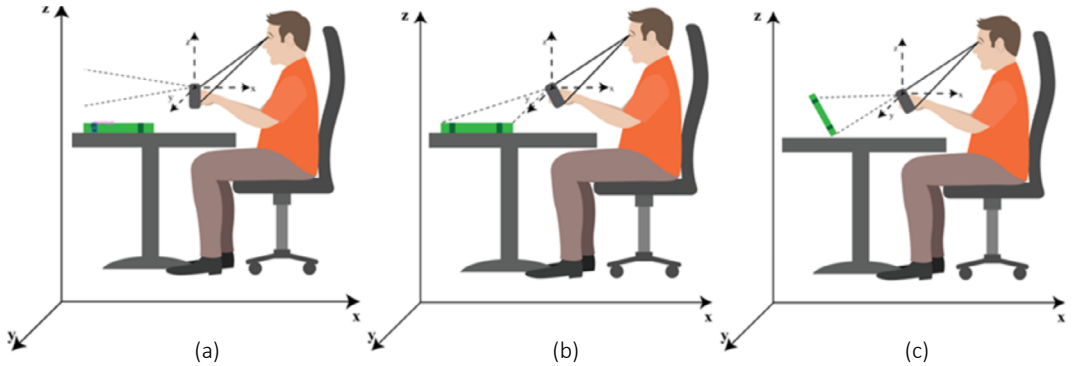
The main goal of this work is to determine the parameters B^* of a multidimensional linear regression model. This model should accurately describe the relationship between the color coordinates of fragments of the color chart used in the AR app content and the color coordinates the user perceives on the smartphone screen. Comparing these values allows us to identify potential color display distortions..

Results

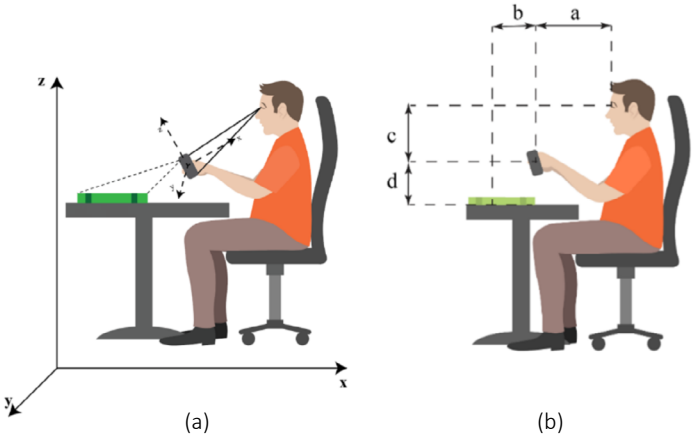
Studying the user's working posture while viewing augmented reality applications on a smartphone

Consider a user sitting and using an AR app with a smartphone and a printed marker on a table (Figure 1). In the default setup (Figure 1a), the phone is vertical and the marker lies flat, forcing the user to view the model from above at an angle.

This hinders interaction and reduces color accuracy. To improve perception, either the phone's angle or marker position should be adjusted (Figure 1b, c), ideally making the marker parallel to the screen to minimize color shifts. Since tilting the marker is impractical without support, the setup in Figure 1b is the most feasible.



» **Figure 1:** *Human posture model and options for placing a gadget or image-tag: a) the marker is horizontal, the smartphone is vertical; b) the marker is horizontal, the smartphone is tilted; c) the marker is tilted, the smartphone is tilted*



» **Figure 2:** *Human posture model and a) convenient placement of the phone; b) image-marker and measurement parameters: distance from eyes to phone a, distance from phone to marker b, height of phone relative to marker d, and height of phone placement relative to eye level c*

For optimal AR use and color fidelity, the model's orientation in virtual space must match the smartphone's tilt relative to the marker. Figure 2 a show an ideal setup, while Figure 2b lists required measurements: user height, arm length, eye-to-phone distance (a), phone-to-marker distance (b), phone height above the marker (d), and phone height relative to eye level (c). To determine the model virtual position, a series of experiments was conducted with the participation of 15 people.

Each participant was given a marker image and a device with an installed augmented reality application. The task was to place the gadget in a position that allows them to comfortably view the virtual model. The following anthropometric indicators were measured: participant height, arm length, distance from eyes to phone *a*, distance from phone to marker *b*, height of phone relative to marker *d*, and height of phone relative to eye level *c* according to Figure 2 b. The height of the table is the same – 74.5 cm. The data entered in Table 1.

Table 1 (part 1)

Results of a study of anthropometric indicators of users viewing an augmented reality application while sitting

Person №	Height, cm	Arm length, cm	Distance from eyes to phone a, cm	Distance from the phone to the mark b, cm	Height of the phone relative to the eyes c, cm	Height of the phone relative to the mark d, cm
1	170	71	33	10	18	21
2	163	68,5	24	9	17	17
3	173	68	32	8	23	16
4	160	67,5	27	13	23	18
5	161	67,5	32	12	16	21
6	158	66	26	10	18	18
7	168	68	29	13	17	18

Table 1 (part 2)

Results of a study of anthropometric indicators of users viewing an augmented reality application while sitting

Person №	Height, cm	Arm length, cm	Distance from eyes to phone a, cm	Distance from the phone to the mark b, cm	Height of the phone relative to the eyes c, cm	Height of the phone relative to the mark d, cm
8	160	66	25	15	20	18
9	155	66	23	8	16	19
10	169	67,5	31	11	16	18
11	157	67	27	12	16	20
12	158	65	24	11	17	17
13	158	65,5	24	12	16	19
14	164	66	24	12	17	17
15	172	70	29	9	19	17

Calculations of geometry of the human body position, showed that the virtual model should be placed in the scene at an angle of 43 to 46 degrees. The distance between AR camera and marker image and model in the virtual scene along the X axis is 37 units, and along the Y axis – 36 units. When adjusting the model's tilt angle, it was discovered that a difference of 2 – 3 degrees does not have a critical impact on result, so the model in the virtual space of AR application was rotated at an angle of 43 degrees.

After that, participants tested augmented reality applications again. According to the test results, it was found that desired effect was achieved in developed applications. As soon as user picked up gadget and launched the application, he/she no longer had to move the phone or marker to find a convenient viewing angle according to the diagram in Figure 2 a.

Development of test objects with color samples

The design of image layouts used as content for augmented reality applications is performed in the RGB color space. This color space is hardware-dependent and represents color reproduction on emissive devices such as computer monitors and smartphone screens. In contrast, human color perception is more accurately described by the CIE Lab color space (International Commission on Illumination, 2004). The RGB and CIE Lab color spaces are nonlinearly related through the intermediate CIE XYZ color space (Hunt, 2004):

$$X = 0.49R + 0.31G + 0.20B \quad (5)$$

$$Y = 0.1769R + 0.8124G + 0.01063B \quad (6)$$

$$Z = 0.00R + 0.01G + 0.99B \quad (7)$$

$$L = 116f\left(\frac{Y}{Y_n}\right) - 16 \quad (8)$$

$$a = 500\left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right) \quad (9)$$

$$b = 200\left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right) \quad (10)$$

$$f(x) = \begin{cases} x^{\frac{1}{3}} & x > 0.008856 \\ 7.787x + \frac{16}{116} & x \leq 0.008856 \end{cases} \quad (11)$$

and X_n=96.4212, Y_n=100, Z_n=82.5188 – color coordinates of the white point D50.

To ensure accurate color reproduction across different devices, color theory and color reproduction practices rely on so-called color profiles. These profiles are based on interpolation tables and are standardized by the specifications of the International Color Consortium (ICC) (International Color Consortium, 2022; International Color Consortium, 2023).

On each device, the color transformations defined by equations (5–11) are performed automatically by dedicated software modules. Consequently, the transformation from the RGB color coordinates of augmented reality content to the CIE Lab coordinates of the colors perceived on a smartphone screen is inherently nonlinear.

In this paper, it is assumed that colors are displayed on the smartphone screen in the augmented reality application has specified RGB_{App} values. According to standard color management models, these values are related to the corresponding Lab_{App} coordinates through equations (5 – 11) (Hunt, 2004).

For the experiment, the selected colors were presented as a chart consisting of uniform color patches. The Pantone Solid Color Set – Formula Guide was used for RGB_{App} (Pantone, 2025) color selection (Figure 3).



» **Figure 3:** *Color palettes for an augmented reality application*

Table 2 (part 1)

Pantone colors for augmented reality applications and their coordinates

Pantone patches for application	Color coordinates of patches						Pantone patches for application	Color coordinates of patches					
	L_{App}	a_{App}	b_{App}	R_{App}	G_{App}	B_{App}		L_{App}	a_{App}	b_{App}	R_{App}	G_{App}	B_{App}
412 PC	19	5	5	55	43	39	358 PC	82	-28	30	165	219	146
447 PC	22	-2	2	50	53	50	406 PC	80	2	2	202	196	194
411 PC	36	6	5	98	82	72	579 PC	83	-11	20	197	213	169
404 PC	49	2	7	124	115	105	698 PC	86	12	0	237	207	215
402 PC	68	2	5	173	165	157	713 PC	83	17	29	251	195	153
7496 PC	53,5	-20,9	51	118	136	29	7492 PC	79,5	-16,4	36,4	191	204	128
5405 PC	40	-8	-19	62	100	126	7544 PC	55	-3,1	-8,4	118	134	146
520 PC	30	34	-28	104	47	115	7516 PC	43,4	24,6	36	153	85	43
484 PC	37	47	36	159	45	32	7459 PC	58,9	-16,8	-22,8	66	152	181
152 PC	61	44	77	231	111	0	7406 PC	80,8	1,8	82,2	241	196	0
102 PC	91	-7	100	250	230	0	7417 PC	53,8	55,3	43,1	224	79	57
121 PC	89	2	57	251	219	110	702 PC	57	47	9	213	100	124
711 PC	47	65	36	211	41	57	603 PC	89	-8	64	237	226	94
627 PC	15	-17	2	3	45	35	564 PC	78	-18	-4	152	204	201
676 PC	35	61	-2	163	0	89	528 PC	57	33	-39	167	116	205
690 PC	27	36	-5	109	35	72	472 PC	70	25	37	228	153	105
581 PC	38	-4	39	96	90	18	435 PC	77	6	-1	200	186	192
5545 PC	43	-15	2	74	109	98	381 PC	84	-22	82	200	219	0
457 PC	62	4	68	178	146	0	116 PC	85	7	93	255	206	0
485 PC	49	68	52	220	36	31	1795 PC	47	68	45	216	31	42
418 PC	38	-2	6	90	91	81	214 PC	45	72	7	208	0	99
Black 3 PC	16	62	65	33	39	33	260 PC	24	37	-25	95	29	95
349 PC	35	-43	18	0	98	51	2597 PC	24	50	-55	89	5	141
322 PC	39	-46	-19	0	111	122	285 PC	48	-3	-58	0	119	212
1545 PC	21	19	26	81	38	11	3288 PC	44	-61	1	0	126	100
165 PC	63	61	75	255	95	0	399 PC	58	-5	72	153	141	0

Table 2 (part 2)

Pantone colors for augmented reality applications and their coordinates

Pantone patches for application	Color coordinates of patches						Pantone patches for application	Color coordinates of patches					
	L_{App}	a_{App}	b_{App}	R_{App}	G_{App}	B_{App}		L_{App}	a_{App}	b_{App}	R_{App}	G_{App}	B_{App}
1935 PC	44	69	23	203	4	71	Wm Gy 11 PC	42,4	3,9	5,5	110	98	89
255 PC	29	40	-25	112	38	108	469 PC	27	19	26	97	52	24
295 PC	17	-2	-39	0	45	98	660 PC	45	2	-51	41	109	193
343 PC	30	-31	5	0	83	62	716 PC	65	42	70	241	124	14
303 PC	18	-15	-22	0	52	77	7547 PC	10,8	-1,1	-9	19	30	41
455 PC	36	2	37	101	84	21	7476 PC	31,4	-18	-8,7	13	82	87
5115 PC	21	21	-8	75	37	62	7528 PC	75,8	2	8,1	197	185	172
7512 PC	48,4	21,7	48,9	166	99	27	7440 PC	55,7	25,1	-18,6	162	119	166
7455 PC	40,9	14,4	-47,1	58	93	174	725 PC	35	30	46	132	59	0
605 PC	81	-5	99	224	202	0	7423 PC	-18,6	52,6	4,2	224	98	135
112 PC	55	2	62	153	128	0	631 PC	69	-27	-23	72	184	210
161 PC	27	18	27	97	53	23	694 PC	66	24	3	202	144	156
1817 PC	24	26	12	94	39	40	569 PC	48	-41	-4	0	132	120
202 PC	31	45	16	137	32	52	555 PC	39	-31	8	19	105	78
2593 PC	35	48	-43	126	43	151	505 PC	27	34	6	110	38	57
274 PC	13	28	-47	33	18	101	4485 PC	32	6	31	93	71	24
3005 PC	44	-23	-60	0	118	204	Pro Yel PC	90,6	-7,2	89,4	254	221	0
369 PC	61	-45	61	79	166	0	137 PC	75	32	87	255	159	0
454 PC	84	-2	10	213	211	191	159 PC	53	45	61	205	88	6
553 PC	25	-16	6	33	66	50	185 PC	50	76	42	234	4	55
583 PC	71	-16	75	171	180	0	2582 PC	48	51	-50	162	76	200
639 PC	56	-38	-42	0	154	207	2655 PC	55	28	-46	145	115	211
141 PC	83	6	53	239	200	104	2718 PC	53	7	-52	84	126	217
182 PC	81	26	0	248	184	203	3262 PC	66	-58	-15	0	186	185
155 PC	87	4	22	236	214	175	360 PC	69	-49	49	85	190	71
2562 PC	73	24	-26	207	165	228	422 PC	69	0	-1	169	170	171
263 PC	84	9	-14	216	203	235	Cl Gy 10 PC	42	-0,7	-3,4	99	102	106
291 PC	80	-9	-20	164	206	236	532 PC	17	1	-10	38	42	57

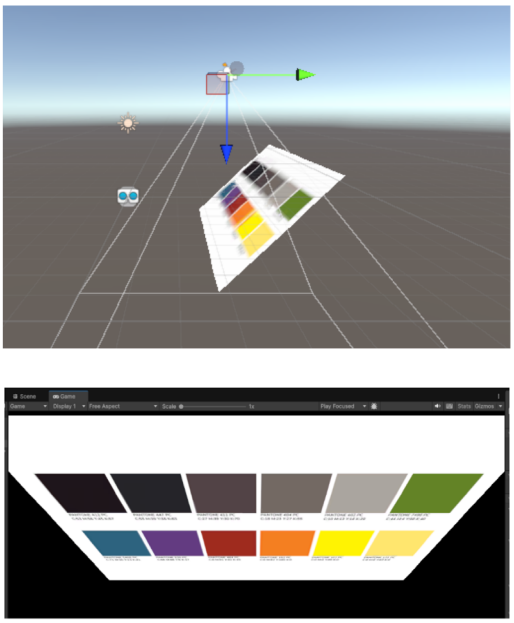
The nine palettes contain 108 colors; they are selected in such a way as to provide uniform distribution in the CIE Lab color space. Five colors in grayscale, saturated and light shades, and midtone gradations are presented here. The color coordinates of the samples are given in Table 2.

Developing an augmented reality application for visual assessment of colors

During development, there was a need to refine the scene geometric parameters to correctly bind a content virtual model to real world. The Unity (Unity Technologies, 2025) environment – a tool designed for creating games and mobile applications – was chosen to develop the augmented reality application.

The development of the augmented reality application in the Unity environment consisted of the following stages: creating a new project and setting the required parameters; adding and configuring a marker image; creating a plane model and specifying its dimensions, position, and viewing angle; placing the plane above the marker at an angle of 43° to improve viewing comfort (Figure 2a); applying the pre-prepared color chart image to the plane model; saving the final version and exporting it in a format compatible with the Android platform.

Initially, all virtual objects were positioned perpendicular to the camera, at a standard scale, and at zero distance from it. During compilation and testing, the smartphone had to be held at a right angle to the marker, which limited the field of view and reduced user comfort. Adjusting the distance between the device and the marker to fully fit the model within the screen further increased user discomfort. To address these issues, the object containing the color chart image (Figure 6a) was rotated by 43° relative to the marker surface. As a result, the augmented reality application, when the smartphone camera is pointed at the marker, displays the color chart at an inclined angle, significantly improving usability and visibility (Figure 4).



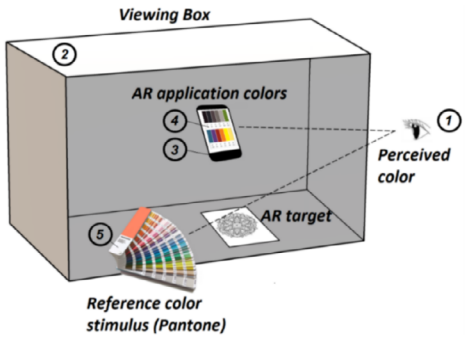
» **Figure 4:** *Rotating the surface of the test object under a cut of 43°*

Visual assessment of test object colors in augmented reality application on smartphone

Under controlled daylight conditions and using a viewing box, the augmented reality application displaying a test object was shown on the smartphone screen in real time. Participants were instructed to observe the image on the smartphone display and visually compare it with a Pantone reference palette, selecting the colors that appeared most similar.

The Pantone Solid Color Set – Formula Guide (Pantone, 2025) was chosen as the reference because its color samples have well-defined color coordinates and are available in physical form for direct visual comparison. Prior to conducting the study, all materials and equipment required for the experiment were prepared in advance.

The following items were used in the experiment: an observer (1), a device with a daylight lamp, a viewing box Just Normlicht Color Viewing light PJC/CVL 5E (2), a smartphone Galaxy A32 (3), an image with labels (4), a Pantone color chart (5) (Figure 5). The Just Normlicht Color Viewing light viewing box allows color evaluation under several standardized illumination conditions, including: D50, D65, F1 – F12, A. The D50 light source is used for experiment.

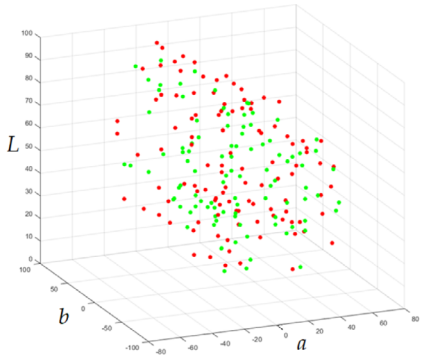


» **Figure 5:** *Scheme of the experiment*

The color coordinates of Pantone Lab $_{Perceived}$ reference patches that visually matched the colors of the test object displayed in the augmented reality application on the smartphone screen were measured using a Gretag-Macbeth Eye-one spectrophotometer.

Multivariate regression model for color transformations in augmented reality application

As a result of the experiment, for each color patch of the test image (which formed the content of the augmented reality application), the visually closest matching Pantone color was selected. Figure 6 illustrates the color coordinates of the test image patches Lab$_{App}$ green dots) and the corresponding Pantone reference colors Lab$_{Perceived}$ (red dots). It is evident that all colors are perceived with some degree of distortion during visual observation.



» **Figure 6:** *Color coordinates Lab$_{App}$ of color patches of image that was the content of augmented reality application (green dots) and visually similar colors Lab$_{Perceived}$ from the Pantone samples (red dots)*

It was hypothesized that Lab_{App} and $Lab_{Perceived}$ color coordinates are related through a linear transformation F. The graphs in Figure 7 show the dependencies of data points

$$\left(L_{Perceived}, a_{Perceived}, b_{Perceived}\right) = F\left(L_{App}, a_{App}, b_{App}\right) \quad (12)$$

and indicate that the transformation F can indeed be approximated as linear.

In this context, the input values (predictors) of a multivariate linear regression model are represented by the set of color coordinates Lab_{App}, while the training values (responses) are the corresponding color coordinates $Lab_{Perceived}$. The model $H: Lab_{App} \rightarrow Lab_{Perceived}$ approximates the target transformation F by minimizing the following least mean squares functional:

$$Q = \sum_{i=1}^{l} \left(H\left(Lab_{App}, B\right) - Lab_{Perceived}\right)^2. \quad (13)$$

where B is the vector of model parameters.

The model H is trained using the least squares method. This approach is justified by the nature of the problem, as matching colors in the Lab color space naturally aligns with minimizing Euclidean distances.

In fact, in color reproduction practice, color differences are typically quantified using the Euclidean distance formula (International Commission on Illumination, 1995):

$$\Delta E_{12} = \sqrt{\left(a_1 - a_2\right)^2 + \left(b_1 - b_2\right)^2 + \left(L_1 - L_2\right)^2} = \\ = \sqrt{(\Delta a)^2 + (\Delta b)^2 + (\Delta L)^2}. \quad (14)$$

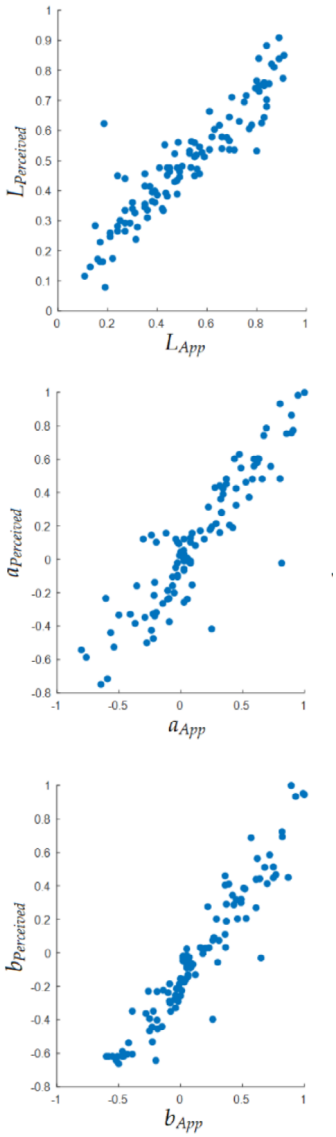
Within this framework, the optimal model parameters minimize the color difference between the augmented reality image content and the colors as perceived by the user on the smartphone screen. The coefficients of the multivariate regression model were determined using two approaches. First, they were estimated via ordinary multivariate normal maximum likelihood estimation applied to the functional in (13). Second, the coefficients were obtained using

$$Q = \sum_{i=1}^{l} \left(H\left(Lab_{App}, B\right) - Lab_{Perceived}\right) C_0 \left(H\left(Lab_{App}, B\right) - Lab_{Perceived}\right) \quad (15)$$

the least squares method with covariance weights (CWLS), which minimizes the objective function

given a fixed covariance C_0.

Additionally, a constraint on the admissible convergence of the log-likelihood objective function was applied to ensure stability. The results of training the model using both algorithms are summarized in Table 3.



» **Figure 7:** *Dependency of color coordinates $L_{Perceived}$, $a_{Perceived}$, $b_{Perceived}$ from L_{App}, a_{App}, b_{pp}*

Table 3

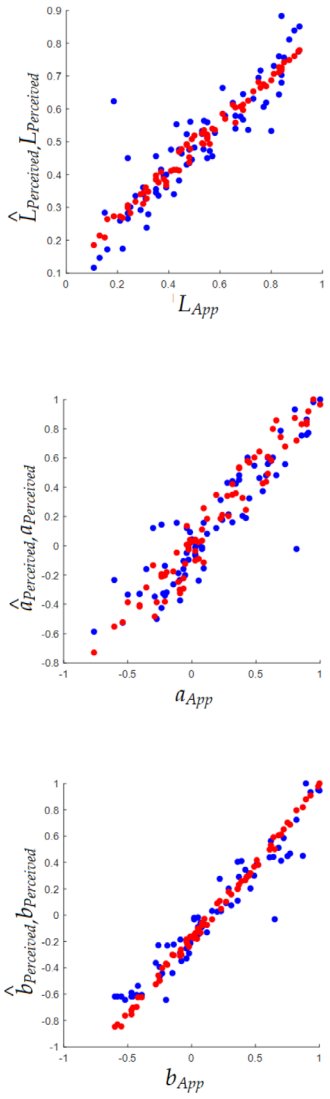
Results of training the multivariate regression model using the ordinary multivariate normal maximum likelihood estimation method and using the least squares method with covariance weights

Algorithm	Number of iterations	Average color error ΔE	The value of the log-likelihood objective function L
Ordinary Multivariate Normal Maximum Likelihood Estimation Method	50	12.6429	-863
	100	13.0471	-832
	150	3.1724	-862
	200	12.5789	-836
Least squares with covariance weights	50	10.1067	-14992
	100	19.7215	-12583
	150	26.5584	-11451
	200	32.1161	-15320

Since in this task the color difference is the most important criterion for assessing the model quality, the best option is recognized as one that provides training of model by the method of usual multivariate normal maximum likelihood estimation over 150 iterations with an average color error ΔE=3.1724. Model weight vector:

$$\boldsymbol{B} = \begin{pmatrix} 0.0299 \\ -0.0246 \\ 0.7591 \\ 0.1337 \\ 0.0371 \\ 0.8361 \end{pmatrix} \quad (16)$$

Figure 8 shows the color coordinates calculated using learned model $h(Lab_{App},B)=\hat{L}\hat{a}\hat{b}_{Perceived}$.



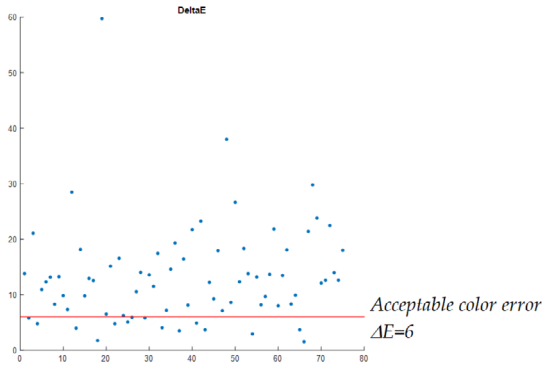
» **Figure 8:** *Dependency of color coordinates $L_{Perceived}$, $a_{Perceived}$, $b_{Perceived}$ from L_{App}, a_{App}, b_{App} (blue dots) and dependency of color coordinates $\hat{L}_{Perceived}$, $\hat{a}_{Perceived}$, $\hat{b}_{Perceived}$ from L_{App}, a_{App}, b_{App} (red dots)*

Typical tolerances in the graphic arts industry usually range between 2 and 6 ΔE. Figure 9 shows the color errors of the predicted colors calculated based on the trained model with coefficients (16). There are 15 colors in the acceptable error range.

Discussion

Experiments measured user posture while viewing AR applications, allowing the placement of 3D models in the virtual space to minimize color distortions caused by viewing angles.

A custom test object – a color chart with predefined colors – enabled objective user-based observation. Color comparisons between the AR app on a smartphone and Pantone samples were conducted in a viewing box under standardized lighting, improving result reliability and reducing variability.



» **Figure 9:** *Color errors for colors predicted by trained model*

The study shows that color distortions in smartphone AR follow consistent patterns that linear models can approximate. The multivariate regression reduces average color error within industry tolerances.

However, color perception is inherently nonlinear and varies across hue regions. This limitation is especially evident for highly saturated colors, where perceptual shifts differ in magnitude and direction. Unlike professional color management systems that rely on thousands of reference samples, this study was constrained to 108 colors, limiting predictive precision.

While neural network approaches could potentially model nonlinearities more accurately, they require substantially larger datasets and longer experimental sessions, making them impractical for this study. The chosen linear regression approach offers transparency, interpretability, and feasibility, making it suitable as a foundational solution.

Limitations of the Study

This study demonstrates that multidimensional linear regression can model color transformations in augmented reality (AR) applications, but several limitations affect its practical use. One key limitation is the small dataset: the model was trained on 108 color samples from nine Pantone palettes to ensure uniform distribution in CIE Lab space. While sufficient to capture general distortion trends, this dataset is much smaller than those used in professional calibration systems and may miss subtle nonlinear effects, especially in highly saturated colors or near the display gamut edges. Expanding to 1,500 – 2,000 samples could improve accuracy.

Another limitation is the use of a single smartphone model. While this reduced variability and ensured consistency, it limits generalization, as different devices vary in display technology, primary colors, gamma, and calibration.

Future studies should include multiple devices to capture device-specific distortion patterns, possibly requiring separate models or adaptive calibration.Experiments were conducted under controlled D50 lighting, which does not reflect real-world conditions where users encounter mixed and dynamic lighting affecting perception. Additionally, linear regression can only approximate perceptual trends; human color perception is inherently nonlinear, so some colors are predicted inaccurately.

Alternative methods – polynomial regression, regularized regression, support vector machines, decision trees, random forests, and neural networks – can model more complex transformations. Support vector machines seem most promising for future research. The study also did not account for individual differences in perception. Overall, the model serves as a baseline but needs refinement and broader testing for high-precision AR applications.

Improvements and Achievements of the Paper

This paper makes several meaningful contributions to the study of color perception and calibration in augmented reality applications by combining empirical experimentation, ergonomic analysis, and interpretable mathematical modeling into a unified framework (Table 4).

This work highlights the integration of user posture and viewing geometry into AR content design. By analyzing anthropometric data and identifying consistent, comfortable viewing positions, the study shows that spatial arrangement of 3D objects can reduce color distortions, complementing algorithmic corrections.

Table 4

Summary Table of Workflow and Results

Stage	Description	Output
Ergonomic study	Analysis of user posture and phone orientation	Optimal viewing angle (43°)
Test object design	Pantone-based color charts	108 reference colors
Visual experiment	AR vs. Pantone comparison under D50 lighting	Perceptual color pairs
Modeling	Multivariate linear regression	Color transformation matrix
Evaluation	ΔE (CIE 1995)	Mean ΔE = 3.17

A controlled perceptual dataset was also created, linking AR-displayed colors to perceived colors under standardized conditions using Pantone references. Though limited in size, it provides a solid empirical basis for modeling color transformations and bridging device-dependent color specifications with human perception.

Additionally, a multivariate linear regression model in CIE Lab space was developed. Unlike black-box approaches, it is interpretable, showing how color components contribute to distortion, achieving an average ΔE of 3.17, within accepted industry tolerances.

Methodologically, the study presents a complete workflow for AR color calibration, including application development, ergonomic optimization, controlled assessment, and modeling. It establishes pathways for improvements such as dataset expansion, cross-device validation, and hybrid modeling, providing a foundation for better color fidelity in mobile AR.

Conclusions

The rise of AR has reshaped online retail by enhancing interactivity and reducing return rates through product visualization. However, accurate color representation remains a challenge, especially in industries like fashion and cosmetics where color fidelity is essential. Color distortions often stem from differences in device displays, lighting, and viewing angles.

This study introduces a multivariate linear regression model to predict and correct AR color shifts, using 108 color patches compared under standardized conditions. The model achieved a mean ΔE of 3.17, showing promise in estimating color deviations. By analyzing posture and viewing angles using anthropometric data, the study proposed ways to improve visual comfort and color fidelity. Despite the model's simplicity and

interpretability, its limited data set restricts precision for professional use. Neural networks may offer better results but require more extensive data.

Future work should expand color samples, include varied devices, and explore hybrid models combining regression with deep learning. Personalized AR interfaces based on ergonomic and perceptual profiles may further enhance accuracy and comfort. This research provides a solid base for improving AR realism and reliability in commercial and broader applications.

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