

Sensor-based Color Design Evaluation Model Integrating Commission Internationale de l'Éclairage $L^*a^*b^*$, Human Perception, and Analytic Hierarchy Process

Siyuan Wang,¹ Hsin-Hung Lin,^{2,3*} Reza Moayer Toroghi,¹
Hwee Ling Siek,¹ and Qi Wang^{1**}

¹Institute of Creative Arts and Design, UCSI University, Kuala Lumpur, Malaysia

²Department of Creative Product Design, Asia University, 500, Lioufeng Rd., Wufeng, Taichung 41354, Taiwan

³Meizhouwan Vocational Technology College, Wutang, Putian 0594-7692626, China

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Color design significantly affects trust in the product and human perception. Existing color design evaluation methods rely on subjective judgment and lack continuous physical spectral grounding. In this study, we developed a sensor-based color design evaluation framework integrating hardware-level optical sensing, Commission Internationale de l'Éclairage $L^*a^*b^*$ color analysis, human perception evaluations, and the analytic hierarchy process. Photodiode arrays (Vishay BPW34) and an STM32F407 microcontroller unit were used to measure real-time surface spectral reflectance and illuminance to compute CIEDE2000 (ΔE_{00}) metrics. A survey of 120 participants across seven perceptual dimensions revealed significant differences ($p < 0.001$), with cool tones outperforming warm tones in cleanliness and purpose. Analytic hierarchy process criteria weighting prioritized purpose (23.68%), safety (19.74%), and cleanliness (17.48%) in selecting colors. The blue–white scheme showed the highest human perception score (5.468), followed by the green–white scheme (5.124). The developed system transforms optical sensors from passive measuring tools into dynamic components for closed-loop, evidence-based healthcare product design and manufacturing quality control. Despite these results, the system needs further improvements to operate under ambient lighting fluctuations. In the following studies, it is necessary to integrate multispectral sensors and longitudinal testing data. The proposed sensor-based framework is relevant to Sustainable Development Goal 9 (SDG 9) through smart-product innovation and may support Sustainable Development Goal 12 (SDG 12) by enabling more consistent, resource-conscious color quality control; actual material savings were not measured in this study.

*Corresponding author: e-mail: hhlin@asia.edu.tw

**Corresponding author: e-mail: qiqiawang960203@gmail.com

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1. Introduction

Advances in AI, IoT, optical sensing technologies, and digital healthcare have accelerated the development of intelligent healthcare products capable of real-time monitoring, data analysis, and remote healthcare services.⁽¹⁾ Although functional sensing, physiological monitoring algorithms, and IoT connectivity are prioritized in smart devices, product appearance design, specifically sensor-based color design evaluation, remains unexplored.

Product color serves as an immediate visual interface that significantly affects user perceptions of purpose, safety, cleanliness, and structural reliability.^(2,3) Existing color design evaluation models rely mainly on static subjective aesthetic feedback or manual offline spectrophotometry. Manual measurement lacks continuous adaptability, fails to account for dynamic environmental lighting fluctuations, and cannot provide real-time objective spectral verification during prototyping or production quality control.^(4,5) In traditional colorimetry, the $L^*a^*b^*$ color space and CIEDE2000 formula (ΔE_{00}) quantify objective color differences.^(6,7)

Established by the International Commission on Illumination, the Commission Internationale de l'Éclairage $L^*a^*b^*$ (CIELAB) color space is a device-independent model representing colors along lightness (L^*), green–red (a^*), and blue–yellow (b^*) to mirror human vision. To quantify visual differences accurately, the CIEDE2000 formula applies parametric weighting factors and interactive rotation terms to compensate for nonlinear human visual perception.^(7,8) However, physical spectral metrics alone cannot capture complex human perceptual, emotional, and cognitive evaluations.⁽⁸⁾ Perception-driven methods lack continuous physical grounding and objective verification. In recent studies, static spectrophotometric measurements or subjective aesthetic evaluations have been conducted,^(9,10) lacking objective evaluation and perception-oriented assessment. To address such limitations, it is necessary to develop an end-to-end, hardware-integrated system that processes optical sensor data in CIELAB colors coordinates. Evaluation indices are also identified to link spectral characteristics to human cognitive perception.⁽¹¹⁾

Therefore, we established a sensor-based color design evaluation system and applied it to the development of a smart pet-caring device. We integrated optical sensor hardware, CIELAB colorimetric transformations, user perceptual evaluations, and the analytic hierarchy process (AHP).⁽¹²⁾ The system employs multi-channel photodiode arrays with optical filters and an analog front-end circuit to continuously capture ambient illuminance and surface spectral reflectance, calculating real-time ΔE_{00} values. The sensor data are merged with multi-criteria human perception scores across seven functional and aesthetic dimensions. AHP weights are integrated into a unified quantitative evaluation score. This calibration and signal processing workflow is applied to the development and assessment of a smart pet-caring device. By automating high-precision spectral extraction, ambient illuminant noise is eliminated, and appropriate product colors are selected with multi-criteria optimization using subjective and experience-driven data. By applying the developed sensor-driven model, optimal visual configurations that maximize user trust, perceived hygiene, and operational safety in real-world environments can be identified in smart manufacturing.

Related research on Internet of Things (IoT)-based pet health and safety monitoring has applied fuzzy analytic hierarchy process evaluation to sensor and hardware requirements⁽¹³⁾.

This provides a complementary perspective on combining sensor-based product functionality with multi-criteria decision-making. In the context of the Sustainable Development Goals, the present color evaluation system is particularly relevant to SDG 9 (Industry, Innovation and Infrastructure), while its prospective application to minimizing manufacturing rework relates to SDG 12 (Responsible Consumption and Production).

2. Method

2.1 System architecture

We developed a sensor-based color design evaluation system by integrating optical sensing, CIELAB color analysis, human evaluation, and AHP, and applied it to a smart pet-caring device. In the system's workflow, sensor data are obtained in the hardware sensing layer from the photodiode array, microcontroller unit (MCU), and optical conversion circuit. The data are processed in the signal processing layer, where CIELAB color coordinates and CIEDE2000 (ΔE_{00}) color-difference metrics are computed. The objective color measurements are integrated with human perception analysis and AHP weighting in the evaluation and decision layer to calculate evaluation scores for color design selection (Fig. 1).

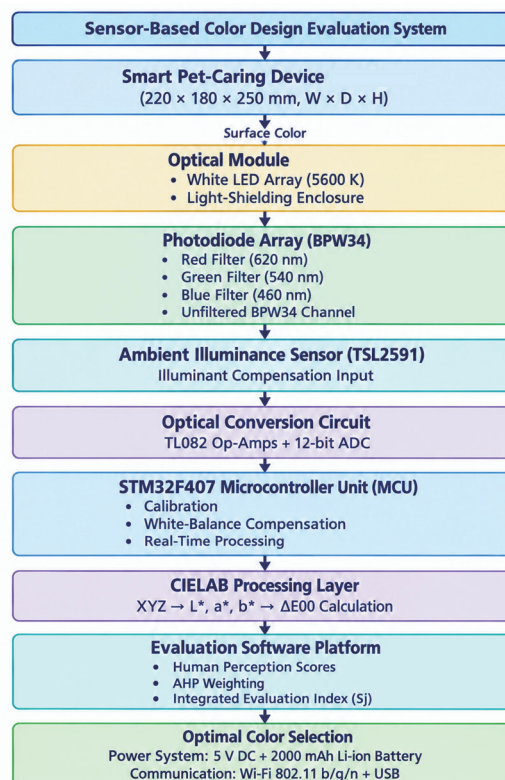


Fig. 1. (Color online) Diagram of system architecture and workflow showing the bottom-up data flow from sensing and processing for perception-based evaluation and decision-making.

Among various color evaluation models, including RGB, hue, saturation, and value, hue, saturation, and lightness (HSL), and Commission Internationale de l'Éclairage L^* , a^* , and b^* (CIELAB, L^* , a^* , and b^* for lightness, green–red, and blue–yellow, respectively), the CIELAB color space was selected in this study owing to its higher device independence and perceptual uniformity.⁽¹⁴⁾ Standard RGB and HSL color spaces are device-dependent and perceptually nonuniform. Their identical coordinate changes do not ensure the detection of equivalent visual changes to the human eye. RGB and HSV lack standardized, nonlinear error-compensation algorithms for quantifying visual deviations. In contrast, CIELAB models human color perception across lightness, green–red chromaticity, and blue–yellow chromaticity. CIELAB aligns with the CIE ΔE (CIEDE2000) color-difference equation, which incorporates lightness, chroma, and hue compensation. The CIELAB mathematical foundation enables the conversion of sensor data to standardized metrics to reflect cognitive human perception under fluctuating ambient lighting.

The hardware layer of the developed system employs photodiode arrays coupled with a conversion circuit to capture spectral reflectance under varying ambient lighting. The circuit was established to convert raw optical signals into standardized CIELAB coordinates. A microcontroller unit was used for sensor calibration, illuminant compensation, and real-time data transmission. The system was deployed on a smart pet-caring device, with embedded optical modules positioned to continuously monitor surface color. In the signal processing layer, the CIEDE2000 color-difference equation is used to quantify perceptual deviations between target design specifications and measured real-time color values. Dynamic white-balance and illuminant compensation routines automatically adjust for ambient light fluctuations. In the evaluation layer, objective sensor data are combined with human perception ratings. Seven evaluation criteria, including purpose, safety, cleanliness, visibility, usability, aesthetic preference, and purchase intention, were identified through a structured questionnaire and weighted using AHP.

The sensor-based color design evaluation system was constructed on a modular hardware platform optimized for real-time optical sensing and data processing. The system includes three main components: photodiode arrays, MCU, and an optical conversion circuit. The system was applied to a smart pet-caring device for automated feeding and basic health-monitoring applications. The device's dimensions were $220 \times 180 \times 250$ mm (width $\times$ depth $\times$ height) and incorporated an enclosed food-storage compartment, a feeding tray, and an exterior housing for color-design evaluation. The device was an application case for validating the developed evaluation system. The system contained the following components:

- Photodiode array and sensor modules: Multi-channel optical sensors [high-speed silicon positive-intrinsic-negative photodiodes (BPW34, Vishay Semiconductor Opto Division, United States)] were used in this study.⁽¹⁵⁾ Each photodiode features a large radiant-sensitive surface area (7.5 mm^2), a broad spectral sensitivity bandwidth (430–1100 nm), peak spectral sensitivity at 900 nm, and a wide viewing angle ($\phi = \pm 65^\circ$). To extract standardized CIE tristimulus colors (X , Y , Z) from raw photocurrents, individual photodiodes in the array are fitted with calibrated optical narrow-band interference filters corresponding to the spectral channels of red [$\lambda_c = 620 \text{ nm}$, full width at half maximum ($FWHM$) = 20 nm], green

($\lambda_c = 540$ nm, $FWHM = 20$ nm), and blue ($\lambda_c = 460$ nm, $FWHM = 20$ nm). To compensate for illuminant fluctuations and background optical noise, an additional unfiltered BPW34 channel is paired with a digital ambient illuminance sensor (dynamic range of 180–88000 lx, TSL2591, OSRAM, Germany). BPW34 is a raw, unfiltered light detector that captures a wide range of light, including invisible infrared light. This arrangement is adopted to monitor background lighting variations and compensate for data in the microcontroller signal processing routines.

- **Optical conversion circuit:** The conversion circuit is included to amplify and filter the photodiode signals before analog-to-digital conversion. It includes precision operational amplifiers (Texas Instruments TL082) and a 12-bit ADC integrated into MCU. The circuit translates optical intensity into standardized CIELAB coordinates, enabling accurate color representation under variable illumination.
- **MCU:** A low-power ARM Cortex-M4 MCU (STM32F407) is used for sensor calibration, illuminant compensation, and data transmission. MCU operates at 168 MHz with 1 MB flash memory and 192 KB random access memory, supporting the real-time computation of the CIEDE2000 formula. Communication between modules is handled using an inter-integrated circuit and universal asynchronous receiver-transmitter protocols.
- **Optical module:** The optical module is included to monitor surface color and transmits data to the processing unit through a wireless interface (Wi-Fi 802.11 b/g/n). The module includes a diffuse illumination source (white LED array, 5600 K color temperature) and a light-shielding enclosure to minimize ambient interference.
- **Power and connectivity:** The system is powered by a 5 V DC supply with a 2000 mAh lithium-ion battery, providing up to 8 h of continuous operation. Data are transmitted to the evaluation software through Wi-Fi or USB for real-time analysis and visualization.

Product color affects the user impressions of healthcare devices, shaping perceptions of professionalism, hygiene, safety, and reliability.^(2,3) Objective color measurement provides quantitative data, but it cannot capture cognitive and emotional responses.⁽⁸⁾ To address this limitation, we combined color metrics with perception-driven evaluation. The CIELAB color space is used for comparing colors. The CIEDE2000 formula is used to refine these comparisons by compensating for nonlinearities in human vision.^(7,8) These metrics are used to quantify differences, but they do not explain how users interpret color in context. Studies show that emotional responses, cultural background, and usage scenarios significantly affect color preference and trust in medical products.^(8,16)

2.2 Evaluation method

On the basis of a comprehensive literature review, seven evaluation dimensions were identified: purpose, safety, cleanliness, visibility, usability, aesthetic preference, and purchase intention. These dimensions capture both the functional and emotional attributes of product color design.^(16,17) To determine the relative importance of these criteria, AHP was adopted. A specialized panel of five experts participated in the pairwise comparison process. The experts were recruited using formal email invitations. They included two industrial designers of medical

device aesthetics and product color planning (12 and 15 years of experience), one optical engineer experienced in sensor calibration (10 years of experience), one human-factors researcher (11 years of experience), and one healthcare product manager (8 years of experience). Each expert independently completed pairwise comparisons using Saaty’s nine-point fundamental scale (Table 1). The consistency ratio (*CR*) was calculated for each matrix to confirm judgment reliability, with all expert evaluations satisfying the threshold of $CR < 0.10$.⁽⁸⁾

To complement the weighting analysis and capture user perceptions of the experts, 120 participants (university students) were recruited. They evaluated the developed system in a controlled lighting laboratory under standardized D65 daylight illumination at 1000 lx. The participants comprised pet owners ($n = 54$, 45.0%), healthcare product consumers ($n = 38$, 31.7%), and students majoring in industrial design and engineering ($n = 28$, 23.3%). The participants’ ages ranged from 21 to 58 years (mean = 34.2, standard deviation = 9.4), including 63 females (52.5%) and 57 males (47.5%). Before evaluation, all participants conducted color-vision screening using the Ishihara pseudoisochromatic plate test to ensure normal color perception. The participants assessed product prototypes with colors calibrated according to the measured CIELAB color parameters using a standardized seven-point Likert scale (1 = strongly disagree, 7 = strongly agree). Evaluations were conducted across the seven predefined perceptual dimensions, and the resulting responses were aggregated to calculate the mean scores and standard deviations for subsequent statistical analysis.

The participants rated each color scheme across the seven evaluation dimensions. Individual participant responses were aggregated into mean scores and standard deviations. The AHP-derived weights were integrated with both the sensor-based ΔE_{00} color-difference values and the 120-participant perception scores to form a comprehensive evaluation index. This multi-methodological approach ensured that objective spectral data, expert criteria prioritization, and broad end-user psychological responses were systematically synthesized into the final design recommendations.

The system was applied to select colors of a smart pet-caring device in six standardized color schemes (white, blue, green, gray, orange, and red). Each scheme maintained identical geometry to isolate color effects. Objective measurements were collected under controlled lighting, followed by human perception experiments with a seven-point Likert scale. Performance evaluation was conducted on (1) the accuracy of real-time color measurement compared with spectrophotometer data, (2) the stability of sensor calibration under varying illuminants, and (3) the consistency of integrated evaluation scores across participants.

Table 1
Saaty’s scale used in pairwise comparison.

Scale	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective.
3	Moderate importance	Experience and judgment slightly favor one criterion over another.
5	Strong importance	Experience and judgment strongly favor one criterion over another.
7	Very strong importance	One criterion is favored very strongly over another; its dominance is demonstrated in practice.
9	Extreme importance	The evidence favoring one criterion over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values	Represent compromise values between two adjacent judgment scales

The structured experiment was conducted in an optical testing laboratory under controlled environmental conditions conforming to the International Organization for Standardization 3664 standards. Lighting was controlled using standard CIE D65 artificial daylight luminaires (1000 ± 50 lx), with a correlated color temperature of 6500 K in a viewing enclosure with neutral matte-gray interior surfaces ($L^* = 50$) (Fig. 2). Five color schemes of the smart-pet-caring devices were shown to match the measured CIELAB surface parameters at a fixed distance of 60 cm.⁽¹⁸⁾ To eliminate sequence bias and visual fatigue, the Latin square design was used to choose the order of color presentations. One hundred twenty participants were randomly assigned to five subgroups ($n = 24$ in each group). The presentation sequence of the five color schemes was structured so that each color scheme appeared once in each ordinal testing position (1st through 5th), ensuring that visual fatigue and sequence bias were evenly distributed in the experiment (Table 2).

2.3 Evaluation metrics

To convert raw photocurrent inputs into objective visual metrics, digitized voltage signals were multiplied by a calibrated spectral transformation matrix M_{trans} to derive CIE values into standard CIE tristimulus values by compensating for photodiode spectral responsivities and LED source emissions.⁽¹⁹⁾



Fig. 2. (Color online) Experimental setup for human perception evaluation of smart pet-caring device color schemes.

Table 2

Counterbalanced presentation order of color schemes using Latin square design in this study.

Subgroup ($n = 24$)	Color scheme 1	Color scheme 2	Color scheme 3	Color scheme 4	Color scheme 5
Group 1	A (blue-white)	B (green-white)	C (gray-white)	D (orange-white)	E (red-white)
Group 2	B (green-white)	C (gray-white)	D (orange-white)	E (red-white)	A (blue-white)
Group 3	C (gray-white)	D (orange-white)	E (red-white)	A (blue-white)	B (green-white)
Group 4	D (orange-white)	E (red-white)	A (blue-white)	B (green-white)	C (gray-white)
Group 5	E (red-white)	A (blue-white)	B (green-white)	C (gray-white)	D (orange-white)

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M_{trans} \begin{bmatrix} V_R \\ V_G \\ V_B \end{bmatrix} \quad (1)$$

Here, X, Y, Z are objective spectral quantities representing visual primary colors, serving as the standardized bridge between raw optical sensor signals and human visual response, V_R, V_G, V_B are digitized analog voltage signals output by the op-amp circuit, proportional to the filtered photocurrents (I_R, I_G, I_B) from the red, green, and blue optical photodiode channels, and M_{trans} is the spectral transformation matrix, a calibrated 3×3 conversion matrix determined for hardware calibration. These values were normalized against reference illuminant coordinates (X_n, Y_n, Z_n) for lighting ($X_n = 95.047, Y_n = 100, Z_n = 108.883$) and converted to $L^*a^*b^*$ coordinates as follows.

$$L^* = 116f\left(\frac{Y}{Y_n}\right) - 16 \quad (2)$$

$$a^* = 500 \left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right) \right] \quad (3)$$

$$b^* = 200 \left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right) \right] \quad (4)$$

The continuous nonlinear transformation function $f(t)$ is defined as

$$f(t) = \begin{cases} t^{1/3}, & \text{for } t > \left(\frac{6}{29}\right)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{16}{116}, & \text{for } t \leq \left(\frac{6}{29}\right)^3 \end{cases} \quad (5)$$

Here, the threshold boundary $\delta^3 = (6/29)^3$ prevents mathematical infinite slope singularities near zero reflectance ($t \rightarrow 0$), ensuring continuous and stable sensor conversion into $L^*a^*b^*$ coordinates across low-light optical conditions. The CIEDE2000 color difference metric (ΔE_{00}) was then evaluated relative to reference scheme parameters using lightness (S_L), chroma (S_C), and hue (S_H) compensation functions, together with the interactive hue-rotation term (R_T).^(6,7)

Each expert independently completed a 7×7 pairwise comparison matrix using Saaty's nine-point fundamental scale. This process required experts to judge the relative importance of each dimension by comparing them two at a time, thereby translating qualitative judgments into quantitative weights. Matrix consistency was validated by computing the maximum eigenvalue (λ_{max}) and the consistency index [$CI = (\lambda_{max} - n)/(n - 1)$]. Reliability was confirmed as all individual consistency ratios satisfied $CR = CI/RI < 0.10$ ($RI = 1.32$ for $n = 7$). To integrate expert judgments, individual matrices were aggregated using the geometric mean method.⁽²⁰⁾

$$a_{ij}^{aggr} = \left(\prod_{k=1}^m a_{ij}^{(k)} \right)^{1/m} \quad (6)$$

Here, a_{ij}^{aggr} is the aggregated relative preference rating between criteria i and j across all experts, $a_{ij}^{(k)}$ is the individual rating assigned between criteria i and j by the k th expert, and m is the number of experts ($m = 5$). Normalized criteria weights (w_i) derived from the principal eigenvector were then combined with real-time sensor ΔE_{00} metrics and normalized Likert perception scores (P_{ij}). This produced the comprehensive color design index (S_j) for each candidate scheme j .

$$S_j = \sum_{i=1}^7 w_i \cdot P_{ij} \cdot \left(1 - \frac{\Delta E_{00,j}}{\Delta E_{max}} \right) \quad (7)$$

This integrated evaluation ensured that both objective spectral data and subjective human responses contributed to the final design recommendations. By involving experts with diverse backgrounds, the weighting process reflected not only technical accuracy but also practical design considerations and user-centered perspectives, strengthening the reliability and applicability of the evaluation model.

3. Results

3.1 Sensor-based CIELAB color measurement

Table 3 shows the sensor-derived CIELAB color measurements for the six color schemes. The CIELAB parameters L^* , a^* , and b^* represent lightness, the green-red axis, and the blue-yellow axis, respectively. The white scheme exhibited the highest L^* value (94.82), indicating exceptional brightness and reinforcing its strong association with hygiene, sterility, and medical cleanliness. Blue and green schemes demonstrated negative a^* values, positioning them within the cool-color region that is commonly related to purpose and safety in healthcare environments. In contrast, the orange and red schemes displayed positive a^* and high positive b^* values, presenting their warm-color characteristics, which enhance visual attention and alertness but may also evoke associations with warnings, risk, or emergencies. The gray scheme was close to the neutral chromatic axis, with minimal a^* and b^* deviations, suggesting a technologically

Table 3
CIELAB color measurement results of product color schemes.

Color scheme	L^*	a^*	b^*	Mean ΔE_{00}
White	94.82	−0.62	2.35	—
Blue	62.45	−8.73	−28.64	27.85
Green	71.36	−24.15	18.27	22.14
Gray	58.91	−0.45	0.98	35.62
Orange	73.18	18.62	42.81	38.47
Red	51.74	42.37	24.68	46.91

neutral and unobtrusive visual appearance. The corresponding ΔE_{00} values indicate substantial perceptual differences among the color schemes between white and red ($\Delta E_{00} = 46.91$) and between white and orange ($\Delta E_{00} = 38.47$), showing that the color alternatives were distinguishable to users. These results show that cool-toned color schemes are appropriate for healthcare-related attributes such as purpose, cleanliness, reliability, and safety, whereas warm-toned color schemes are for enhancing visibility and attracting user attention.

The system also computed perceptual differences using the CIEDE2000 formula. The largest ΔE_{00} values were observed between white and red (46.91) and between white and orange (38.47), indicating strong perceptual contrast. Smaller differences between blue and green (22.14) confirmed their similarity as cool colors. Figure 3 shows the distribution of the six color schemes in the CIELAB space. White is positioned centrally with high lightness, blue and green cluster in the cool-color quadrant, orange and red occupy the warm-color region, and gray remains close to neutrality. This distribution demonstrates that the sensor system enables a clear, reproducible separation of color categories relevant to healthcare design. Overall, the sensor data validate the system's ability to deliver accurate, real-time CIELAB measurements and perceptual difference calculations, forming the quantitative foundation for subsequent perception analysis.

3.2 Perception evaluation

Table 4 shows the perception evaluation results for the six color schemes in seven dimensions. Scores are reported as mean values $\pm$ standard deviations based on a seven-point Likert scale (1 = strongly disagree, 7 = strongly agree). Higher mean scores indicate a positive user perception of a given attribute, whereas lower mean scores represent weaker associations with that attribute. The white and blue color schemes showed the highest scores in purpose, safety, cleanliness, usability, aesthetic preference, and purchase intention. This indicates that these cool-toned color

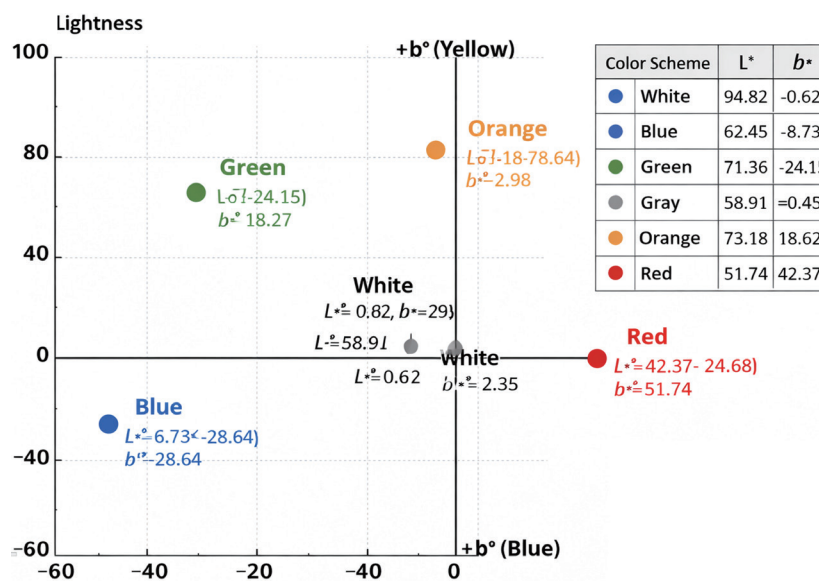


Fig. 3. (Color online) Proposed color schemes in CIELAB color space.

Table 4
Human perception evaluation results of product color schemes.

Evaluation dimension	Score (mean $\pm$ standard deviation)					
	White	Blue	Green	Gray	Orange	Red
Purpose	6.58 $\pm$ 0.49	6.42 $\pm$ 0.55	5.91 $\pm$ 0.68	5.43 $\pm$ 0.73	4.82 $\pm$ 0.81	4.35 $\pm$ 0.88
Safety	6.46 $\pm$ 0.53	6.31 $\pm$ 0.58	6.12 $\pm$ 0.61	5.39 $\pm$ 0.77	4.71 $\pm$ 0.83	4.22 $\pm$ 0.91
Cleanliness	6.71 $\pm$ 0.41	6.35 $\pm$ 0.56	6.08 $\pm$ 0.64	5.36 $\pm$ 0.75	4.63 $\pm$ 0.86	4.18 $\pm$ 0.93
Visibility	5.84 $\pm$ 0.66	5.97 $\pm$ 0.61	5.73 $\pm$ 0.70	5.12 $\pm$ 0.79	6.44 $\pm$ 0.48	6.68 $\pm$ 0.42
Usability	6.12 $\pm$ 0.58	6.03 $\pm$ 0.62	5.91 $\pm$ 0.65	5.52 $\pm$ 0.71	5.26 $\pm$ 0.76	5.04 $\pm$ 0.82
Aesthetic preference	6.18 $\pm$ 0.55	6.11 $\pm$ 0.57	6.04 $\pm$ 0.60	5.48 $\pm$ 0.73	5.56 $\pm$ 0.69	5.21 $\pm$ 0.77
Purchase intention	6.21 $\pm$ 0.57	6.09 $\pm$ 0.61	5.96 $\pm$ 0.64	5.33 $\pm$ 0.75	5.18 $\pm$ 0.79	4.89 $\pm$ 0.84

schemes are related to purpose, cleanliness, usability, and purchase intention in healthcare-related products. In particular, the white color scheme obtained a high cleanliness score (6.71 $\pm$ 0.41), emphasizing its association with sterility and medical hygiene. The green color scheme showed high scores, especially for safety and cleanliness, indicating that it conveys a sense of comfort and reassurance.

In contrast, the orange and red color schemes showed lower scores in purpose, safety, and cleanliness, despite achieving the highest visibility scores. The red scheme obtained the highest visibility score (6.68 $\pm$ 0.42), followed by orange (6.44 $\pm$ 0.48), showing that warm colors are effective in attracting visual attention. However, their low scores in trust-related dimensions show that increased conspicuity degrades the original purpose of the product and hygiene-related dimensions. The gray color scheme showed intermediate scores in most dimensions, reflecting a neutral and technologically oriented appearance but less healthcare-related dimensions than the white, blue, or green color schemes. In summary, cool-toned color schemes are more appropriate to show an impression of safety, cleanliness, and reliability of healthcare products, whereas warm-toned color schemes are more appropriate when visual prominence and attention capture are the main design objectives.

ANOVA results showed statistically significant differences ($p < 0.05$) across most dimensions, indicating that product color exerts a measurable effect on human perception (Table 5). The results revealed statistically significant effects of color scheme ($p < 0.001$) for all evaluation dimensions. Specifically, perceptual differences were pronounced in cleanliness [$F(5595) = 184.12$, $\eta_p^2 = 0.607$], purpose [$F(5595) = 142.85$, $\eta_p^2 = 0.546$], and safety [$F(5595) = 126.41$, $\eta_p^2 = 0.515$], where cool-toned color schemes (white and blue) significantly outperformed warm tones. In contrast, visibility exhibited an inverse trend [$F(5595) = 118.90$, $\eta_p^2 = 0.500$], with warm-toned color schemes (red and orange) scoring highest in visual attention. Significant variations were also confirmed for usability, aesthetic preference, and purchase intention ($p < 0.001$). The ANOVA results show that product color exerts a measurable and systematic effect on user cognitive evaluation, establishing a rigorous empirical basis for the subsequent AHP weighting model.

Figure 4 shows the comparison of human perception evaluation results in the proposed color schemes. White demonstrated balanced performance across all dimensions, blue excelled in professionalism and reliability, green scored well in safety and comfort, whereas orange and red dominated visibility but underperformed in trust-related dimensions.

Table 5
Summary of one-way ANOVA results for product color schemes ($N = 120, p < 0.001$).

Evaluation dimension	Mean square (MS)	F -value	η_p^2
Purpose	38.42	142.85	0.546
Safety	35.18	126.41	0.515
Cleanliness	44.25	184.12	0.607
Visibility	22.84	118.9	0.505
Usability	11.53	45.62	0.277
Aesthetic preference	9.87	38.19	0.243
Purchase intention	18.21	71.34	0.375

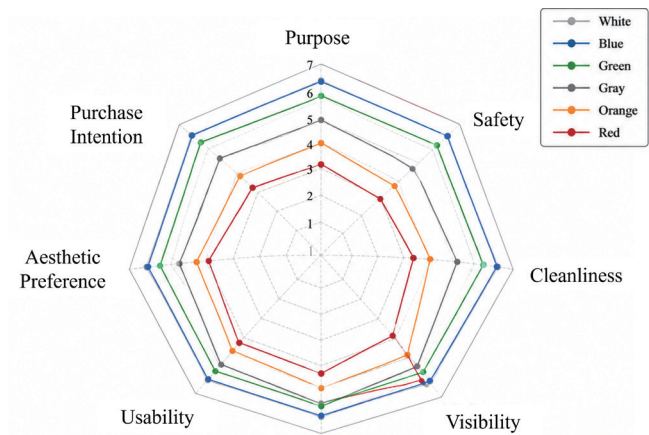


Fig. 4. (Color online) Radar chart of human perception evaluation results for proposed color schemes.

Expert evaluation results using AHP showed the relative importance of the seven dimensions. Figure 5 shows the hierarchical structure and Table 6 presents the normalized weights. Purpose (23.68%), safety (19.74%), and cleanliness (17.48%) were observed as the most critical dimensions. Visibility, usability, aesthetic preference, and purchase intention followed with lower weights. Consistency testing results showed $CR < 0.10$, validating the reliability of expert judgments.

The AHP weights were integrated with perception scores and sensor-derived ΔE_{00} values to calculate comprehensive scheme scores. White achieved the highest score (6.370), followed by blue (6.236) and green (5.970) (Table 5). Gray ranked fourth, while orange and red, despite strong visibility, scored lowest owing to weaker performance in professionalism, safety, and cleanliness. Table 7 shows the evaluation workflow and ranking outcomes. Cool-color combinations (blue–white, green–white) consistently outperformed warm-color alternatives, confirming that sensor-based measurement combined with perception analysis and AHP weighting provides a robust framework for healthcare product color design.

The sensor data confirmed that each of the six proposed color schemes exhibited distinct CIELAB characteristics, with reliable ΔE_{00} differences observed across schemes. These objective measurements demonstrated the system’s ability to capture reproducible and meaningful distinctions in lightness, chromaticity, and perceptual color difference. The human perception results were consistent with the sensor outputs, showing that participants generally

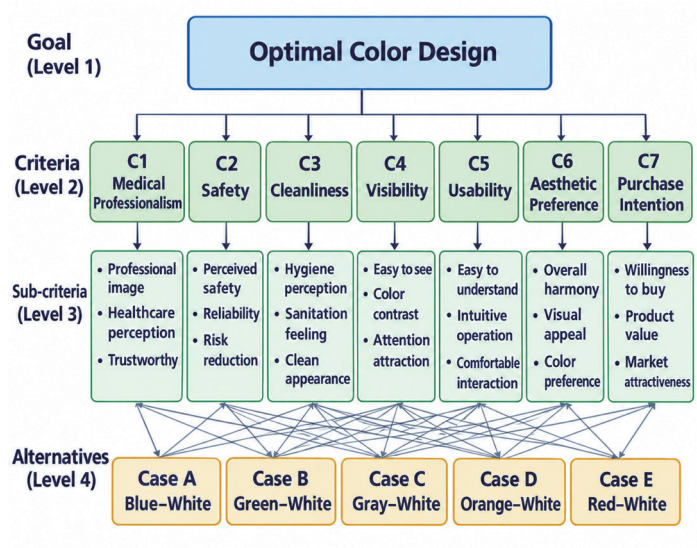


Fig. 5. (Color) Evaluation results of proposed product color design using AHP.

Table 6
AHP weights and rankings of color design evaluation criteria.

Evaluation dimension	Normalized weight	Percentage (%)	Rank
Purpose	0.2368	23.7	1
Safety	0.1974	19.7	2
Cleanliness	0.1748	17.5	3
Visibility	0.1397	14.0	4
Usability	0.1031	10.3	5
Aesthetic preference	0.0770	7.70	6
Purchase intention	0.0711	7.11	7
Total	1	100	

Table 7
CIELAB color measurement parameters and ΔE_{00} values for five product color schemes (cases A–E).

Case	L^*	a^*	b^*	ΔE_{00} (compared with Case A)
A (blue–white)	88.36	−8.21	−20.15	0
B (green–white)	87.54	−12.45	9.32	6.28
C (gray–white)	81.21	−1.03	−2.15	4.35
D (orange–white)	82.47	15.36	31.42	18.72
E (red–white)	78.63	33.28	13.26	23.16

preferred cool colors such as white and blue in healthcare contexts. These colors were associated with professionalism, safety, and cleanliness, while warm colors such as red and orange were more strongly linked to visibility and visual attention. AHP weighting results showed that professionalism, safety, and cleanliness are the most effective criteria in the evaluation model. This prioritization reflected expert consensus that healthcare product design should primarily convey trust, hygiene, and reliability.

In the evaluation, sensor data, perception ratings, and AHP weights were integrated to identify white and blue as the optimal color schemes, with green emerging as a strong alternative. Orange and red, although effective in visibility, were less favored owing to lower ratings in professionalism and cleanliness. The results show that the developed system integrates objective sensor measurements with subjective perception data and expert weighting. The system was used to select colors of a smart pet-caring device, ensuring that both technical accuracy and user experience are incorporated into final design recommendations.

To obtain the evaluation index for each two-tone color scheme, the mean human perception ratings (x_{ij}) were calculated. The ratings were multiplied by their corresponding normalized AHP expert weights (w_i) using the weighted-sum model.

$$S_j = \sum_{i=1}^7 w_i \cdot x_{ij} \quad (8)$$

Table 8 presents the complete perception scores, AHP criteria weights, and resulting weighted scores across the five product color schemes (Cases A–E). Case A (blue–white) achieved the highest overall score (5.468), performing strongly across the top-weighted criteria: purpose (6.32), safety (6.21), and cleanliness (6.18). Case B (green–white) ranked second (5.124), showing particular strength in aesthetic preference (5.12) and purchase intention (4.88). Although Case D (orange–white) and Case E (red–white) rated high in visibility (6.12 and 6.53, respectively), their significantly lower ratings in medical trust dimensions reduced their weighted scores (3.924 and 3.553, respectively). The results showed that warm-toned color schemes effectively attract visual attention and cool two-tone color schemes provide a more effective balance for healthcare product applications where safety, hygiene, and clinical reliability are paramount.

4. Discussion

We developed a sensor-based color design evaluation system that integrates objective optical measurements, human perception experiments, and expert weighting using AHP. The results demonstrated a strong correspondence between sensor-derived spectral characteristics (L^* , a^* , b^* , ΔE_{00}) and user evaluations across key dimensions such as purpose, safety, and cleanliness.

Table 8
Human perception scores, normalized AHP weights, and weighted scores for color schemes.

Evaluation criterion	A (blue–white)	B (green–white)	C (gray–white)	D (orange–white)	E (red–white)	Normalized AHP weight
Purpose	6.32	5.91	4.98	3.21	2.87	0.228
Safety	6.21	5.88	4.76	3.18	2.65	0.185
Cleanliness	6.18	5.74	4.55	3.01	2.48	0.158
Visibility	4.86	4.48	4.02	6.12	6.53	0.129
Usability	5.02	4.86	4.28	4.21	4.03	0.113
Aesthetic preference	4.96	5.12	4.35	4.21	3.61	0.111
Purchase intention	4.61	4.88	3.92	3.45	3.12	0.080
Weighted score	5.47	5.12	4.40	3.92	3.55	1.00

Color schemes with higher lightness values (L^*) measured by the sensor consistently achieved higher ratings for cleanliness and professionalism, confirming that sensor outputs can predict perceptual associations with hygiene and trust. These results align with previous research showing that lightness strongly affects perceived sterility and clinical rigor. Cool-toned color schemes (white and blue) were consistently favored in healthcare contexts, while warm-toned color schemes (orange and red) enhanced visibility but reduced perceptions of reliability.⁽¹⁵⁾

By integrating hardware-level sensing with structured human perception scoring, the system establishes a quantitative, evidence-based framework for healthcare product design. The sensor data provide reproducible, standardized inputs, while perception experiments capture cognitive and emotional responses, ensuring that both objective and subjective dimensions are represented. The optical sensor plays a role in color design evaluation. First, it ensures precise data collection and calibration, enabling the accurate monitoring of surface reflectance and maintaining consistency across manufacturing batches and lighting conditions. Second, it provides standardized input, delivering deterministic chromaticity parameters (L^* , a^* , b^*) that eliminate subjective ambiguity and feed directly into the AHP weighting model.⁽²¹⁾

The AHP results showed that purpose (23.7%), safety (19.7%), and cleanliness (17.5%) were dominant criteria, accounting for more than half of the total decision weight. This prioritization indicates that in healthcare-related hardware, users value functional trust and perceived clinical safety over aesthetic novelty. The sensor ensures that these high-weighted dimensions are objectively quantified, strengthening the reliability of the integrated evaluation.

The integrated color design evaluation framework yielded scores that combined sensor-calibrated color data, perception ratings, and AHP weights. Cool-color combinations, particularly blue–white and green–white, consistently outperformed warm alternatives. Blue–white achieved the highest ranking owing to its balanced performance across professionalism, safety, and cleanliness, confirming its appropriateness for a smart pet-caring device. The system also demonstrates broad applicability in industrial engineering and man–computer interaction.

- Automated quality assurance: Manufacturers can deploy the sensor-based telemetry framework on production lines to monitor batch-to-batch color drift (ΔE_{00} tolerance checks), ensuring consistent product quality and psychological impact.⁽⁷⁾
- Smart medical devices: The methodology can be extended to human medical devices, geriatric care robotics, and assistive technologies, where user trust, visibility, and emotional reassurance are critical for adoption.
- Healthcare product design: By integrating sensor data with perception and expert weighting, the system provides a replicable model for evidence-based design decisions in healthcare environments.

The developed system proves that sensor technology is not only a measurement tool but also an essential component of multi-criteria color design evaluation. By combining objective spectral data, subjective perception ratings, and expert prioritization, the system provides a rigorous, reproducible, and user-centered approach to color design in smart pet healthcare products. This integration ensures that design recommendations are both technically accurate and psychologically validated, offering a pathway for broader application in healthcare product innovation.

Sensor-network optimization for automated chip sorting and carbon-emission reduction provides a related example of fuzzy multi-criteria decision-making in sustainable industrial applications⁽²²⁾. Multicultural design research on Malaysian Ang-Pow also highlights the potential importance of cultural context in visual interpretation⁽²³⁾, supporting future cross-cultural testing of color preferences. These links provide a rationale for SDG 9 and SDG 12 applications; however, the present experiment did not directly quantify emissions, waste reduction, or life-cycle impacts.

5. Conclusion

A sensor-based color design evaluation system is developed in this study by integrating hardware optical sensing, CIELAB colorimetry, human perception evaluation, and AHP. The system establishes a closed-loop, data-driven methodology that bridges physical spectral measurements with cognitive user evaluations. Through the integration of multi-channel photodiode arrays (Vishay BPW34) and operational circuits, the system enables the real-time extraction of surface spectral reflectance and automated conversion into CIELAB coordinates (L^* , a^* , b^*) under variable ambient illuminance. The continuous computation of CIEDE2000 (ΔE_{00}) color difference values enables the measurement of precise chromatic deviations relative to reference baselines, such as white ($L^* = 94.82$) and red–white ($\Delta E_{00} = 23.16$). This eliminated the limitations of static offline measurement and reduced the effect of illuminant noise, thereby ensuring stable and reproducible sensor outputs.

Human perception testing results with 120 participants using a seven-point Likert scale showed statistically significant variance across seven visual and functional dimensions ($p < 0.001$). High-lightness, cool-toned color schemes consistently outperformed warm-toned alternatives in trust-related attributes, showing the largest effect sizes in cleanliness. In contrast, warm-toned color schemes such as red and orange dominated visual attention but yielded lower scores in perceived hygiene and safety.

The AHP weighting results showed that purpose (23.68%), safety (19.74%), and cleanliness (17.48%) emerged as the three most influential criteria, collectively accounting for 60.90% of the total decision weight. A CR value lower than 0.10 indicated the reliability of the expert matrix. When spectral data, perceptual scores, and AHP weights were synthesized, the two-tone blue–white scheme achieved the highest integrated performance index (5.468), followed by green–white (5.124), gray–white (4.404), orange–white (3.924), and red–white (3.553).

The results of this study serve as a basis for the application of sensor technology in product engineering and human–computer interaction. The system demonstrates how optical sensing hardware can transition from a passive quality-control instrument into an active, multi-criteria decision engine for user-centered design. By embedding photodiode arrays with onboard MCU signal processing, the system enables real-time ambient illuminant compensation and spectral error detection. Furthermore, the methodology provides a replicable blueprint for automated inline telemetry, enabling the continuous monitoring of color drift during manufacturing. This ensures that healthcare devices, medical robotics, and assistive technologies maintain both visual trust and psychological efficacy. Despite the results, limitations of this study must be

addressed. Since ambient lighting fluctuations can degrade sensor performance in extended use, multispectral optical sensors and machine learning algorithms must be integrated for adaptive light compensation. It is also necessary to test the developed system with multi-textured materials.

The system also offers a potential contribution to Sustainable Development Goal 9 (SDG 9) by advancing sensor-enabled design evaluation and intelligent manufacturing. Future assessments of manufacturing waste, color-related rework, and life-cycle performance are required to determine whether it contributes measurably to Sustainable Development Goal 12 (SDG 12).

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About the Authors



Siyuan Wang is a Ph.D candidate at the Institute of Creative Arts and Design, UCSI University, Kuala Lumpur, Malaysia. His research interests include fashion design, aesthetic studies, and cultural and creative product design, related to visual hierarchy, information presentation, and the integration of aesthetic and functional considerations in digital and smart product design. (wangsiyuan0614@gmail.com)



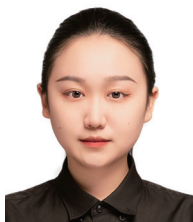
Hsin-Hung Lin is a professor in the Department of Creative Product Design at Asia University, Taichung, Taiwan, and also serves as a professor at the Institute of Creative Arts and Design at UCSI. His major research interests include fuzzy set theory in product design, concurrent engineering, computer-aided design, neural networks and gray theory, color planning, heat transfer analysis, and reverse engineering in product development. (hhlin@asia.edu.tw)



Reza Moayer Toroghi is an Assistant Professor at the Institute of Creative Arts and Design, UCSI University, Kuala Lumpur, Malaysia, and serves as the Head of Programme for the Master of Art, Design and Creative Media. He holds a PhD in Public Art. His research interests include fine art, mural art, cross-cultural studies, and symbolism. (rezamt@ucsiuniversity.edu.my)



H wee-Ling Siek is an associate professor at the De Institute of Creative Arts and Design, UCSI University, Kuala Lumpur, Malaysia and serves as Deputy Director and Head of Research in the faculty. Her research interests span cultural design, graphic design, sustainability, computer-aided design, and creative heritage practices. She is committed to advancing academic and creative communities through collaborative and practice-led approaches. (siekhl@ucsiuniversity.edu.my)



Qi Wang is a Ph.D. candidate at the Institute of Creative Arts and Design, UCSI. Her research focuses on user interface design and interaction-oriented visual design, with particular emphasis on interface aesthetics, visual hierarchy, information presentation, and user-centered digital design. (qiqiawang960203@gmail.com)