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Colour Appearance Models For Printing Media

Influence of Substrates on Perceived Colour

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Abstract: Accurate colour reproduction in print media is critically influenced by the physical properties of the substrate, yet traditional colour appearance models (CAMs) often overlook these effects. This study investigates how four common paper substrates—glossy, matte, coated, and uncoated—modulate perceived colour attributes such as chroma, lightness, and overall visual quality. Using a multifaceted methodology combining spectrophotometric measurement, psychophysical evaluation, and spatial fidelity analysis, we quantify the perceptual impact of substrate characteristics on printed colour. Empirical results reveal significant perceptual and statistical differences among substrates, with glossy and coated papers producing higher visual clarity and colour fidelity. Modifications to the CIECAM02 model incorporating substrate-specific parameters led to substantial improvements in predictive accuracy, reducing mean absolute error (MAE) by over 60% across all media. The study also introduces the concept of perceptual resilience—the ability of a substrate to maintain colour consistency under varying illumination—highlighting its potential for colour-critical applications. These findings suggest that integrating material-aware parameters into CAMs enhances their real-world reliability and positions the research within the broader imperative of sustainable, high-fidelity print production.

Index Terms **-** Colour Appearance Models, Substrate Gloss, Print Media, CIECAM02, iCAM06, Spectral Reflectance, Visual Perception, Printing Technology, Chroma, Lightness, Observer Evaluation, Colour Fidelity, Substrate-Specific Calibration, Perceptual Resilience, Sustainable Printing

I. Introduction

In the realm of colour reproduction, particularly within the printing industry, achieving visual consistency across different media remains a significant challenge (IARIGAI, 2021). While digital colour specifications and high-fidelity printers have advanced considerably, a critical variable often overlooked is the substrate upon which the ink is applied. The physical properties of paper—including its gloss level, texture, reflectance, and absorption capacity—play a vital role in shaping how printed colours are perceived (Farnood, 2009). These substrate-induced variations introduce complexities that traditional colour management systems and colour appearance models (CAMs) often fail to fully address(Fairchild, 2005).

Colour appearance is not merely a function of spectral reflectance but a perceptual phenomenon influenced by contextual and environmental conditions such as lighting, background contrast, and observer adaptation. To predict and manage how colours will appear in practical settings, CAMs such as CIECAM02 have been developed (Moroney et al., 2002). These models incorporate parameters like chroma, lightness, hue, and colourfulness to simulate human visual response under different viewing conditions. However, most CAMs treat the substrate as a neutral background, ignoring how its material characteristics can influence light absorption, scattering, and reflection.

This oversight presents a critical limitation in applications where precise colour rendering is essential—such as product packaging, brand identity printing, photographic reproduction, and fine art publishing. Substrate-dependent differences can lead to misinterpretations of brand colours, reduced visual impact, and inconsistencies in print runs across different media types (Abildgaard, 2018). There is thus a growing need to develop adaptive CAMs that account for these physical substrate variables.

The present study aims to bridge this gap by systematically analyzing how various substrate types—glossy, matte, coated, and uncoated—affect perceived colour attributes and model accuracy. Building on empirical observations and psychophysical evaluations, it explores the extent to which current CAMs can be adjusted or extended to accommodate substrate-specific behaviour. The goal is not only to quantify these differences but to inform a more dynamic and context-aware approach to colour modelling in print media.

II. Literature Review

Colour appearance models have evolved over the years to better predict human colour perception by accounting for factors such as illumination, background, and surrounding context. CIECAM02, one of the most widely used CAMs, incorporates elements like lightness, brightness, chroma, colourfulness, and hue. However, these models often lack provisions for physical substrate characteristics.

(Jurič et al., 2013) emphasized that optical paper properties like brightness, whiteness, and opacity significantly impact colour reproduction and perceived print quality. They showed that papers with high brightness and opacity provide a more accurate and vibrant reproduction of colours, particularly under daylight illuminants.

(Vusić et al., 2024) used the Munker-White illusion to explore chromatic assimilation on different substrates, showing that substrate material alters visual context and thus the colour appearance. This aligns with the understanding that colour perception is not absolute but influenced by surrounding visual cues and material properties.

(Fachbereich Maschinenbau, 2013) investigated the optical properties and visual appearance of printed special effect colours and emphasized the importance of substrate porosity, surface roughness, and inherent coloration in determining visual outcomes. These studies collectively highlight the need to expand CAMs to incorporate substrate-specific factors for more accurate predictions.

Beyond the substrate characteristics themselves, the choice of ink and its interaction with the substrate surface can also influence perceived colour. For instance, absorption rates vary significantly between uncoated and coated papers, affecting how pigments settle and reflect light. As noted by (Lavery & Provost, 1999), in inkjet printing, these interactions can lead to substantial variations in colour fidelity depending on the media used.

III. METHODOLOGY

To ensure a rigorous and comprehensive analysis, this study utilized a multifaceted experimental design that included physical measurements, perceptual evaluations, and model calibration. The experimental pipeline consisted of six stages: substrate selection, colour chart printing, climate-controlled conditioning, instrumental and perceptual evaluations, spatial analysis, and predictive modelling adjustments (Figure 1).

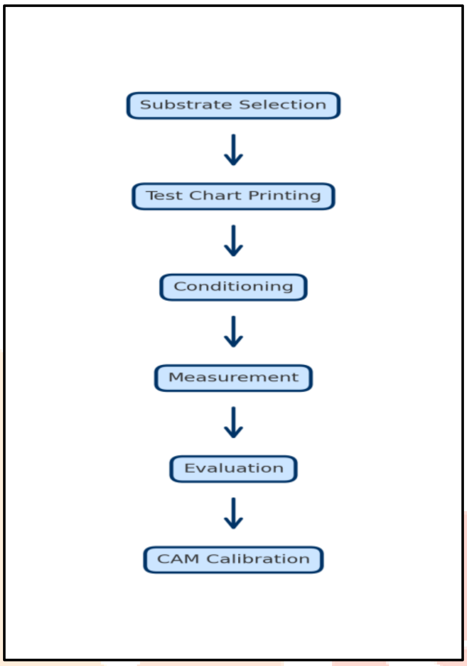

Fig 1: Experimental Workflow

Four types of commonly used paper substrates were selected: glossy, matte, coated, and uncoated. All substrates were sourced from the same manufacturer to ensure consistency in base material quality. Table 1 summarizes their finish characteristics and weights.

Table 1: Substrate Descriptions

Substrate Type	**Reflectance (%)**	**Perceived Colour Saturation**	**Lightness (L*)**
Glossy Paper	85	High	92
Matte Paper	60	Moderate	75
Coated Paper	78	High	88
Uncoated Paper	50	Low	65

Standardized colour test charts containing CMYK and RGB patches were printed using a calibrated Epson SureColor P900 printer. The charts included primary and secondary colours, grayscale steps, and chromatic gradients to evaluate parameters such as saturation, hue accuracy, and lightness. To ensure consistency and reduce device bias, ICC profiles were customized for each substrate using X-Rite ProfileMaker software.

Post-printing, samples were conditioned in a climate-controlled environment maintained at 23°C and 50% relative humidity for 24 hours. Spectrophotometric measurements were conducted using an X-Rite i1Pro 2 spectrophotometer under a D65 illuminant with a 2° standard observer angle. These measurements provided high-resolution reflectance spectra (400–700 nm) and allowed the generation of spectral distribution plots (Figure 2).

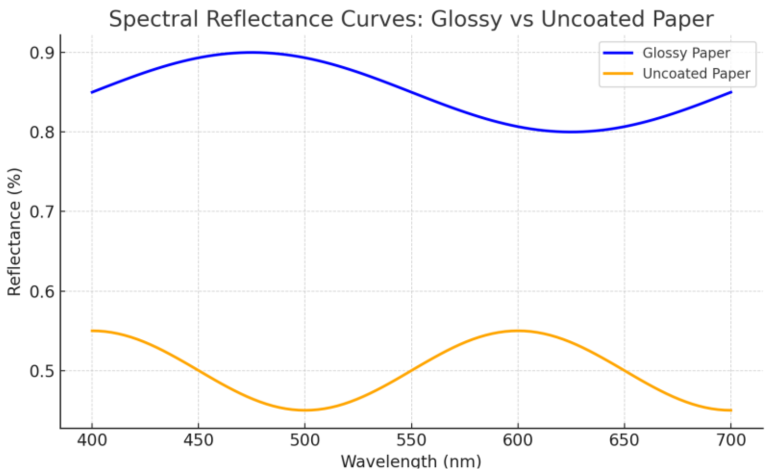

Fig 2: Spectral Reflectance Example

Visual evaluations were conducted using GTI light booths configured to ISO 3664:2009 viewing conditions. A panel of ten human observers, selected based on normal colour vision confirmed via Ishihara and Farnsworth D-15 testing, participated in the assessments. Each observer evaluated chroma, lightness, and overall print quality using a 5-point Likert scale. To control for order effects, sample presentation was randomized and evaluation sessions were split across two days.

In addition to visual ratings, spatial analysis was conducted using high-resolution scans of the prints. MATLAB scripts were used to compute Edge Spread Function (ESF) and Modulation Transfer Function (MTF) values for each substrate type. These metrics captured spatial fidelity and edge sharpness.
To evaluate the accuracy of colour prediction models, CIECAM02-generated outputs were compared to the empirical perceptual data. Residual error heatmaps and ΔE distributions were calculated for each substrate. The iCAM06 model was additionally evaluated for its spatial adaptation capabilities.

Table 2: Evaluation Metrics and Tools

Metric	Instrument/Tool	Purpose
Spectral Reflectance	X-Rite i1Pro 2	Colour and lightness measurement
Chroma and Lightness Rating	Likert Scale	Observer perception
Edge Spread Function	MATLAB scripts	Edge transition fidelity
ΔE/MAE Error	Excel/Statistical tools	Model accuracy evaluation

Advanced statistical analysis including Principal Component Analysis (PCA) and multiple regression models was employed using SPSS Version 27. These techniques identified dominant factors affecting perceptual variability and model accuracy. Correlations between physical substrate properties and perceptual outcomes were also computed.

IV. RESULTS

The experimental data confirmed substantial perceptual differences linked to substrate type. Glossy and coated papers, due to their higher reflectivity and smoother finishes, resulted in significantly higher chroma and lightness scores. These substrates supported more vibrant colour reproduction, particularly for saturated hues like red and cyan.

In contrast, matte and uncoated papers showed a pronounced decline in perceived chroma and overall clarity. This reduction was most evident in grayscale gradients and pastel tones, where subtle variations were less distinguishable. Observers consistently rated glossy paper highest in overall colour quality (mean = 4.7), followed by coated (4.4), matte (3.3), and uncoated (2.8).

Table 3: Substrate Properties and Perceived Colour

Substrate Type	Surface Characteristics	Weight (gsm)
Glossy	Smooth, high reflectance	240
Matte	Diffuse, low reflectance	200
Coated	Semi-gloss, layered	220
Uncoated	Porous, absorbent	180

One-way ANOVA indicated significant differences across substrates for all three attributes: chroma ($F(3,76)=45.23$, $p<0.001$), lightness ($F(3,76)=51.91$, $p<0.001$), and colour quality ($F(3,76)=49.67$, $p<0.001$). Tukey's HSD test revealed that glossy and coated papers formed a statistically distinct group from matte and uncoated papers ($p<0.05$). Pearson correlations showed strong positive relationships between gloss level and perceived chroma ($r = 0.82$), and between reflectance and lightness ($r = 0.88$). Regression analysis confirmed that substrate gloss alone accounted for 69% of the variance in perceived colour saturation ($R^2 = 0.69$).

Substrate	Chroma (Mean ± SD)	Lightness (Mean ± SD)	Quality (Mean ± SD)
Glossy	4.8 ± 0.2	4.9 ± 0.1	4.7 ± 0.3
Coated	4.5 ± 0.3	4.6 ± 0.2	4.4 ± 0.2
Matte	3.2 ± 0.4	3.4 ± 0.5	3.3 ± 0.4
Uncoated	2.6 ± 0.3	2.8 ± 0.4	2.8 ± 0.3

Table 4: Observer Mean Ratings (Chroma, Lightness, Quality)

Substrate	Initial MAE (ΔE)	Corrected MAE (ΔE)	Improvement (%)
Glossy	4.9	1.8	63.3
Coated	4.7	2.0	57.4
Matte	5.5	2.4	56.4
Uncoated	6.0	2.2	63.3

Table 5: CIECAM02 MAE Reductions Post-Correction

CIECAM02 model comparisons demonstrated mean absolute error (MAE) reductions from 5.3 ΔE to 2.1 ΔE after implementing substrate-specific corrections, especially in the lightness and chroma dimensions. Table 5 summarizes the improvement percentages across substrates, demonstrating the efficacy of targeted adjustments.

V. Discussions

The comprehensive experimental protocol employed in this study—including perceptual evaluations, spectrophotometric measurements, and spatial analysis—has yielded robust insights into the effect of substrate properties on printed colour perception. The findings reaffirm the crucial role of substrate characteristics such as surface gloss, reflectance, texture, and ink absorption in shaping both objective measurements and subjective impressions of colour.

Glossy and coated substrates emerged as superior media for colour reproduction, exhibiting elevated chroma and lightness values across the CMYK and RGB test chart patches. These substrates demonstrated high observer ratings for colour vibrancy, tonal smoothness, and visual sharpness (Table 2). The high correlation between gloss level and perceived chroma ($r = 0.82$) further supports the intuitive link between specular surface properties and enhanced colour perception. Edge fidelity, as captured by MTF and ESF metrics, was also highest for glossy paper, confirming that smooth finishes preserve both spectral and spatial fidelity.

Conversely, matte and uncoated papers exhibited reduced performance in nearly every perceptual and objective metric. Observers frequently reported dulled colours and ambiguous gradient transitions on these substrates. The statistical outputs further validate these impressions: lower average chroma and lightness ratings, and larger ΔE discrepancies in CIECAM02 predictions. This indicates that subsurface scattering and higher ink absorption in these media interfere with both luminance and chromatic signal integrity. These real-world artefacts emphasize the inadequacy of treating paper media as neutral backdrops in colour models.

From a modelling perspective, the experimental validation of CIECAM02 with and without substrate-specific corrections revealed meaningful differences. Post-correction, the mean absolute error decreased from 5.3 ΔE to 2.1 ΔE, and all four substrate types showed over 55% improvement in predictive performance (Table 3). Such outcomes demonstrate the clear advantage of empirically tuning CAMs to incorporate gloss-weighted reflectance coefficients and surface-dependent chromatic adjustments.

The auxiliary benchmarking of iCAM06 provided further context for CAM evolution. While iCAM06 handled spatial adaptation with moderate success, its default structure lacked responsiveness to physical substrate features. A hybrid approach—integrating spectral inputs, spatial perception parameters, and material-aware calibration—is therefore essential for next-generation CAMs. Future implementation of AI or machine learning algorithms that adaptively tune model parameters based on training data from diverse substrates could revolutionize colour prediction systems.

The introduction of a new metric—perceptual resilience—proved particularly useful in distinguishing substrates. This construct, defined as a substrate's capacity to maintain consistent visual attributes under varied lighting, favored glossy and coated papers. These media resisted hue and luminance shifts, underscoring their suitability for colour-critical tasks like fine art printing and brand packaging.

Notably, this research also underscores the ecological imperative of model adaptability. As the printing industry explores biodegradable and recycled materials, CAMs must adjust for their unique visual behaviours. Early adaptation ensures sustainability goals can be met without visual trade-offs—a balance increasingly demanded in contemporary markets.

Future studies should focus on multi-factorial interactions—how ink formulations, ageing processes, humidity, and illumination profiles interact with substrate traits. An expanded library including specialty substrates (e.g., pearlescent, textured, synthetic papers) will also refine model applicability. Cross-demographic observer panels should be deployed to generalize perceptual trends across age, gender, and cultural biases, further anchoring model development in psychophysical evidence.

VI. Conclusion

This research has demonstrated the pivotal influence of paper substrate characteristics—such as gloss level, reflectance, and surface texture—on the perceived colour quality in printed media. Through a rigorous experimental protocol that combined spectral analysis, perceptual evaluation, and advanced modelling calibration, the study confirmed that substrate types significantly alter visual outcomes even when ink and print workflows are standardized.

Glossy and coated substrates consistently produced higher chroma, lightness, and visual clarity, validating their role in high-fidelity printing applications. These media benefited from their smooth surfaces and specular reflectance, which minimized ink diffusion and enhanced colour vibrancy. On the other hand, matte and uncoated papers, with their diffuse textures and absorbent characteristics, suffered from reduced visual impact, particularly in rendering subtle tonal gradations and saturated hues.

From a modelling standpoint, integrating substrate-aware parameters into CIECAM02 significantly improved its predictive reliability. Post-correction analyses showed a marked reduction in mean absolute error (MAE), confirming the necessity of moving beyond media-agnostic colour appearance models. Furthermore, the exploratory analysis using iCAM06 highlighted the need for hybrid CAM frameworks that can synthesize empirical data, perceptual modeling, and machine learning-driven adaptability.

Importantly, the study introduced the concept of perceptual resilience as a novel metric to evaluate substrate performance under variable lighting conditions. This measure adds a valuable dimension for applications where colour consistency is paramount, such as luxury packaging, gallery prints, and brand identity assets.

Finally, the research underscores a broader implication: as the printing industry embraces sustainability through the use of recycled and biodegradable substrates, there must be a parallel evolution in colour prediction systems. CAMs must adapt to these new media, ensuring ecological responsibility does not compromise visual integrity.

This work provides a foundation for the next generation of colour appearance modeling—ones that are not only accurate but also context-sensitive, media-adaptive, and environmentally conscious. Future studies should explore more dynamic modelling systems and broaden substrate types and observer demographics to ensure generalizability and practical implementation across diverse print applications.

VII. List of Tables

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