Color-Printed Gloss: Relating Measurements to Perception

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Abstract
In order to assess the print quality, color and gloss are two important factors that should always be considered. In this paper, we investigate the impact of color on gloss using printed color samples varying between low and medium gloss levels. A psychophysical experiment was conducted to relate specular gloss measurements to perception. Results show that second order polynomials describe well this relationship independently of the underlying color. Following the same trend for all colors, the magnitude of perceived gloss decreases with increasing lightness.

Introduction
In general color and gloss are two important attributes which are related to the surface optical properties, the visual perception and the illumination condition. Hunter was the first who found the multi-dimensionality of gloss and defined six gloss attributes which describe human's gloss perception [1]. Various other studies confirm a multidimensionality of gloss perception [2, 3]. In this work, we focus on *specular gloss* which is measured by taking the ratio of the reflected light from the surface to the incident light with the same angle to the surface normal and in comparison with a reference sample [4]. The final term reads:

$$\text{Specular Gloss} = 100\frac{\Phi_{\theta,\textit{Test sample}}}{\Phi_{\theta,\textit{Reference sample}}} \qquad (1)$$

where $\Phi_{\theta,\textit{Test sample}}$ and $\Phi_{\theta,\textit{Reference sample}}$ refer to the emitted flux of the test and reference samples and θ refers to the angle of incident and reflected light measured to the surface normal [4, 5]. Gloss meters measure the glossiness of the surfaces in comparison with a mirror-like black glass with refractive index of 1.567 as the reference sample and in specular gloss units (GU). The GU of 100 is defined for this reference sample for any angle of illumination [5]. For specular gloss measurements, the most common angles of illumination are 20, 30, 45, 60, 75, and 85 degree which among them 20, 60, 75, and 85 degree are the most common ones in the printing industry [4]. Some research has been conducted mostly in the area of computer graphics and printing in order to investigate gloss perception and the impact of gloss on color. Ji *et al.* [5] found that the relation between the visual gloss scale data and the gloss measurements can be described by a three-part linear or by a polynomial of degree three. This finding was also mentioned by Obein *et al.* [6] and Billmeyer and O'Donnell [7]. Although many of the previous works were based on achromatic samples, some experiments were conducted for both achromatic and chromatic cases [5].

Baar *et al.* [8] proposed two novel print modes for generating matt and glossy prints using a 2.5D or relief printing system which relies on a layer-by-layer basis. Utilizing one print mode, local gloss levels were controlled by changing the ink deposition time between two layers of white ink. Another print mode enabled printing matt surfaces by controlling the order on which the pixels are printed. Since for generating surfaces with different gloss levels the same colorant coverage and percentages were utilized, printing local gloss variations without differential gloss artifacts become possible. Gloss values of the printed samples were measured using the *BYK Gardner Micro-Tri-Gloss* gloss meter. Based on these gloss measurements for 60° specular gloss, surfaces from approximately 0.7 to 18.1 GU could be printed. A gloss rank order psychophysical experiment was also conducted in order to compare perceived gloss ranks with the rank order results achieved by the gloss meter. An average Spearman Correlation of 0.8139 for all of the printed samples was reported which showed that gloss levels are ranked almost similar by humans and measurements. Moreover, an average of 57% of the observers agreed upon the change of color between the samples printed with the same colorant combination and percentages while having different gloss levels. This result showed that, as with many other applications, color and gloss can not be treated separately in such printing systems [8].

In this work, we investigate the interaction of color and gloss in 2.5D printing system by conducting and evaluating a gloss scale psychophysical experiment.

Psychophysical experiment
In order to investigate the effect of color on gloss, we conducted a gloss scale psychophysical experiment in a completely darkened room and inside a viewing booth employing CIED65 illumination. All remaining lights were switched off to avoid any unwanted stray light.

2.5D test samples
The test samples that we used for this experiment were the same as those utilized for the rank order psychophysical experiment in [8]. These samples were printed with the size of approximately 1.5"x3.5" using the 2.5D printing mechanism and two print modes. The first one is based on the deposition of two white layers and the top color layer using Cyan (C), Magenta (M), and Yellow (Y) inks. By controlling the time between the deposition of the two base white layers we printed 2.5D samples with different gloss levels. This print mode is denoted as *gloss mode*. The second mode is called *matt mode*. The deposition order of C, M, and Y inks is changed in multi-pass printing resulting in a uniformly matt appearance. We created seven different colorant combinations (C, M, Y) = (100, 0, 0)(= **C**), (0, 100, 0)(= **M**), (0, 0, 100)(= **Y**), (0, 100, 100)(= **R**), (100, 0, 100)(= **G**), (100, 100, 0)(= **B**), (100, 100, 100)(= **K**).

For each colorant combination six samples varying in gloss lev-

Test set	CIEL*	CIEa*	CIEb*	CIEDE00
C	54.38	-27.84	-44.79	0.98
M	41.46	69.45	-10.17	1.03
Y	88.10	-15.40	93.80	0.56
R	41.57	57.01	33.32	1.83
G	48.78	-71.24	30.76	1.44
B	21.60	24.59	-35.94	2.29
K	22.68	-0.38	0.26	3.82

Table 1. The averaged CIEL*a*b* values together with the averaged CIEDE00 color-differences calculated for all of the samples in each test set.

els were printed one in matt mode and five in gloss mode. In total, seven test sets with six samples per set, i.e. 7x6 = 42 test samples, were used for conducting the psychophysical experiment. For the sake of simplicity, we call the test sets by the abbreviations mentioned above. The 6 samples in each set are denoted by **M**, **G1**, **G2**, **G3**, **G4**, and **G5** from the lowest to highest expected glossy surface where **M** and **G** refer to *Matt* and *Gloss*, respectively. The average color coordinates for each test set are listed in Table 1. Note that the color variations within each test set are rather small.

Since the assessment of multiple viewing and illumination geometries is simultaneously possible using cylindrical shapes, we glued the test samples to cylindrical gray tubes with the diameter of approximately 1.3 inches. Enough margin was considered for each sample to avoid fingerprints to be left on the surfaces.

Reference samples

For the reference samples we utilized 5 samples out of the available 28 samples of the NCS Gloss Scale. The chosen samples were all medium gray (NCS S 5000-N) ranging from full matt to semi-gloss with visually equal gloss steps. Table 2 depicts the reference samples with their names and gloss values at 60° specular gloss according to the NCS Gloss Scale product description. These samples are also illustrated in figure 1. It should be mentioned that we also measured the gloss values of the reference samples with the *BYK Gardner Micro-Tri-Gloss* gloss meter at 60° specular gloss. The deviations were found to be small with the maximum of 2.5 GU for the matt sample.

Figure 1. *The reference samples.*

The reference samples were cut in the same size as the test samples and also glued on cylindrical gray tubes with similar diameters as the test samples. Moreover, in order to have consistent conditions the reference samples were interconnected and placed at a fixed position in the viewing booth. Observers were not allowed to move

NCS reference sample name	Gloss value - 60°
1. Full Matt	2
2. Matt	6
3. Semi-Matt	12
4. Satin Matt	30
5. Semi-Gloss	50

Table 2. The five medium gray reference samples chosen from the NCS gloss scale patches.

them. Since the purpose of this psychophysical experiment was to acquire the perceived gloss scales, we assigned the numbers of 1 to 5 to the reference samples.

Task

The test samples were selected and gave to the observers randomly and one-by-one. The observers were asked to compare each test sample with the reference samples and give a scale value according to the reference gloss scale they perceived similar to the test sample. The scale was virtually extended on both ends to allow assignments with smaller and larger gloss values than in the NCS scale. Assignments of intermediate gloss values were allowed in 0.5 steps, i.e. $0.5, 1, 1.5, \ldots, 5, 5.5$. The observers used a chin rest and hold the test samples at their arm's length. They were allowed to tilt the samples only in the direction of the reference samples and inside the viewing booth to decide upon each sample's glossiness. The distance from the observer's eye to the reference and test samples was approximately 23 inches. The following figure illustrates the experimental setup. In total, 15 color normal observers (9 male, and 6 female) with ages ranging from 21 to 56 participated in the experiment. The normal color-vision of each observer was tested prior to the experiment using the Ishihara Color Vision Test and Farnsworth-Munsell Dichotomus D-15 Test in the same viewing booth.

Figure 2. *The psychophysical experiment setup.*

Results and Discussion

To evaluate the perceived gloss scales given by the observers, we computed for each sample a mean value from 15 observations. The maximum and minimum standard deviations were 0.9741 and 0.2211 respectively. A second degree polynomial was used to fit the data because of its higher coefficient of determination ($\mathbf{R^2} = 0.8529$)

Test set	Coefficient of determination R^2
C	0.99
M	0.99
Y	0.96
R	0.94
G	0.94
B	0.98
K	0.98

Table 3. The coefficients of determination R^2 for the fitted curves (second degree polynomials) for the mean data in each test set.

in comparison with Linear regression ($\mathbf{R^2}$ = 0.7010), Gaussian ($\mathbf{R^2}$ = 0.8358), Exponential ($\mathbf{R^2}$ = 0.6022), and Power ($\mathbf{R^2}$ = 0.8047) functions. Figure 3 shows the calculated mean gloss scale values together with the fitted curve as a function of visual gloss scale data vs. specular gloss value measurements for 60° specular gloss.

As expected, this curve shows an increase of gloss scales given by observers; i.e. in general from the lowest to the highest gloss value the perceived glossiness of the samples has increased. A slightly decreasing trend is visible nearly at the highest measured specular gloss. This is caused by yellow samples that were perceived less glossy even though the measured values are larger than the others. This indicates that a more accurate psychophysical transformation from specular gloss measurements to perceived gloss should also consider color attributes.

Since the 2.5D printing system was able to print samples up to approximately 18.1 GU for 60° specular gloss, it is impossible to compare our results with other work for higher gloss values. However, our results show a good agreement with gloss curves presented in literature for the investigated gloss range [5, 9, 6].

Effect of color on gloss

In order to investigate the influence of color on the gloss perception all mean visual gloss scale data points for each set of color samples were plotted and fitted by a second degree polynomial function (parabola). This function was chosen because of its higher coefficients of determination $\mathbf{R^2}$ for mostly all data sets in comparison with Linear regression, Gaussian, Exponential, and Power functions. Table 3 shows $\mathbf{R^2}$ values for the fitted curves for all test sets.

As figure 4 illustrates, the trend of the curves is almost similar independently from the underlying color. This agrees with results found in literature [5]. It should be mentioned that the cyan curve shows a slightly different behavior at the near end of the graph in comparison with the other curves. We don't have any specific explanation for this drop of perceived gloss.

Finally, we observed that samples with higher lightness are perceived less glossy, as can be seen clearly for the yellow samples. This might be caused by the smaller luminance contrast between the specular and off-specular angles. The corresponding visual attribute -gloss contrast- cannot be meaningfully related to specular gloss measurements but has likely an impact on observer judgments. Figure 5 shows lightness vs. perceived gloss. The scale values are averaged over each sample's observations. For illustrating the decrease of perceived gloss with increasing lightness, we fitted a trend line (also a second degree polynomial) to the data.

Conclusions

In this work, we investigated the impact of color on gloss for 2.5D prints, varying between low and medium gloss levels. For this, we conducted and evaluated a gloss scale psychophysical experiment. In our point of view the effect of color on gloss could be explained better by considering the general *glossiness trend* and the *perceived gloss value*. Based on our experiment, the color has not showed to be an influencing factor on the general glossiness trend; i.e. this trend could be explained as almost an increasing function of perceived gloss scales and gloss measurements regardless of the samples' color which is well described in the above mentioned gloss range by a second degree polynomial. On the other hand, although lighter samples have the same general glossiness trend, they were perceived less glossy than the darker ones. This result could be explained by the fact that specular gloss highlights have a larger contrast on darker samples. In future work, we aim to include more samples with gloss variations between medium to high created by a different 2.5D printing system in order to evaluate the complete gloss range. Furthermore, we aim to develop a color-gloss gamut mapping algorithm to account for the dependency of gloss and lightness interaction.

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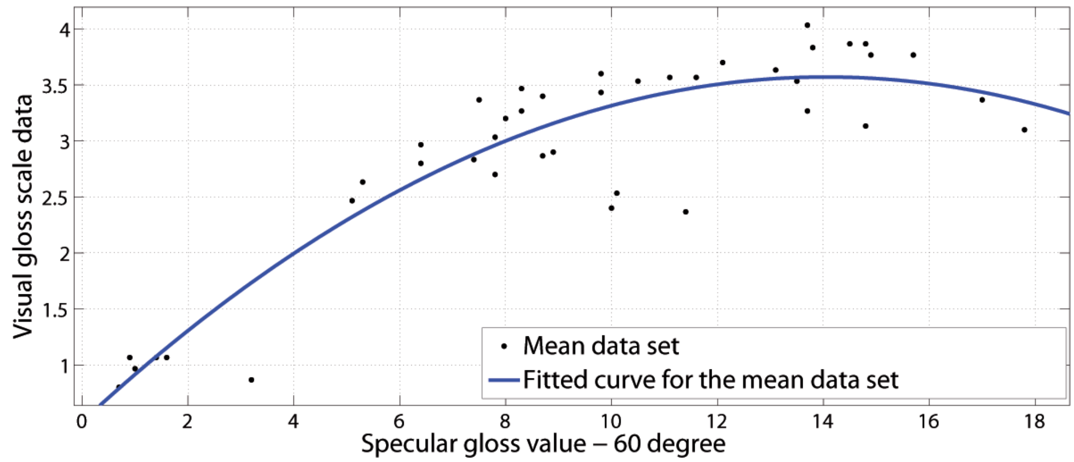

Figure 3. *Averaged visual gloss scale data vs. 60° specular gloss measurements.*

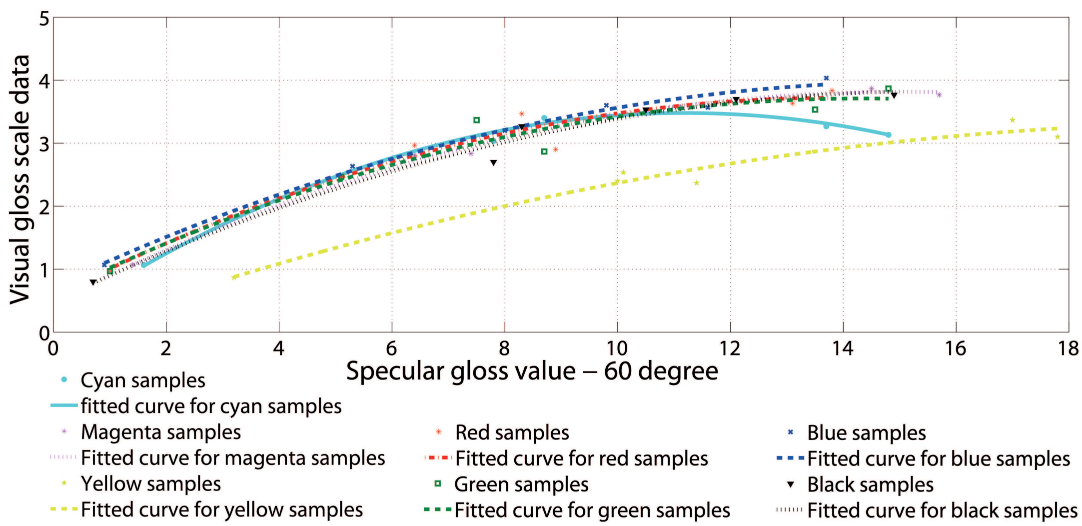

Figure 4. *Separately fitted curves for all data sets:* ***C***, ***M***, ***Y***, ***R***, ***G***, ***B***, *and* ***K***.

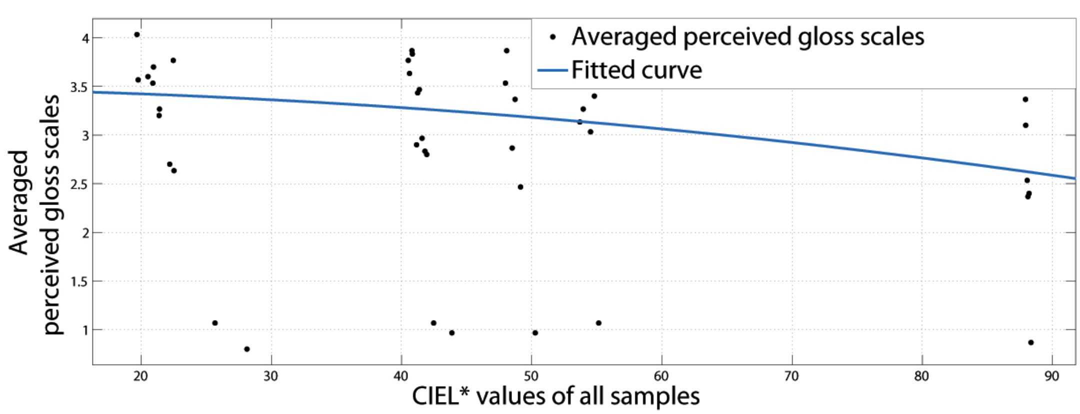

Figure 5. *The averaged perceived gloss scales vs. the samples' CIEL* values. The averaged perceived gloss scales were calculated for each of the test samples in each test set considering 15 observations. The lightness values were computed from the measured reflectance data and for the CIED65 illuminant and 2° standard observer.*

Author Biographies

Sepideh Samadzadegan started her research at Technische Universität Darmstadt (Germany) since 2012 as an EU-researcher involved in the Colour Printing 7.0 | Next generation multi-channel printing (CP 7.0) project. Her research focus is on color science specifically spectral gamut prediction and mapping as well as printing gloss effects using 2.5D printing technology. She holds MSc in Media Technology and Engineering (Advanced Computer Graphics) from Linköping University, Norrköping Campus, Sweden.

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Philipp Urban received the M.S. degree in mathematics from the University of Hamburg, Germany, in 1999 and the Ph.D. degree from the Hamburg University of Technology in 2005. From 2006 to 2008, he was a Visiting Scientist with the Munsell Color Science Laboratory, Center for Imaging Science at the Rochester Institute of Technology in Rochester NY and headed afterwards the Color Research Group at the Institute of Printing Science and Technology, Technische Universität Darmstadt, Germany. Since 2013 he has been Head of the Competence Center 3D Printing Technology at the Fraunhofer Institute for Computer Graphics Research IGD in Darmstadt. His research interests include spectral imaging, image quality and material appearance reproduction.