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A Model of Visual Opacity for Translucent Colorants

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Abstract

Potential methods for predicting the visual impression of the opacity of translucent white ink were evaluated. An experiment was conducted to collect visual data for white ink coatings on three different substrates: white paper, clear film and kraft paper. The contrast ratio metric used for paint and varnish coatings, together with other proposed methods, were tested as correlates for the visual data. The contrast ratio, based on the difference in reflectance between ink printed on the substrate and over a black ground, performed most consistently across the three substrates, while other correlates, such as relative lightness or colour difference, performed better for ink on certain substrates. The results also indicate that a method that does not use black ground under the coating may provide better results when the substrate differs significantly in appearance from the ink.

Introduction

Opacity is an appearance attribute, also referred to in industrial applications as hiding power or solidity. In optics, opacity is a measure of impenetrability to radiation, including visual light. Hence, an opaque material transmits no light, which is the opposite property of transparency. A translucent material on the other hand, both transmits and reflects incident light, i.e. translucency is an optical property, with transparency and opacity on opposite ends of its scale [9]. Opacity is defined as a material property called the mass attenuation coefficient, κ_ν, which determines the intensity of a beam of light within a material:

$$I(x) = I_0 e^{-\kappa_\nu \rho x}, \tag{1}$$

where x is the distance through a medium that light has travelled, $I(x)$ is the intensity of light remaining at distance x, and I_0 is initial intensity of light at $X = 0$, ν is the frequency of the light, and ρ is the density of the mass. Opacity has a numerical value between 0 and infinity for a given medium at a given frequency.

Ink are translucent colorants, and the level of opacity of the ink determines the ink's ability to cover the backing it is printed on. The translucent property of ink determines how the colorants will visually interact with the colourants of the backing. Knowledge of ink opacity is therfore crucial for determining the outcome of for example spot colour overprints, which are widely used in packaging [7], or the physical result of using pdf blend modes in graphical software. Thus, models for ink opacity are needed to ensure that printed products will match the intended graphical design. There are ISO methods for the determination of hiding power of paint and varnish coatings, [3] [4], based on the contrast ratio between measurement for paint/varnish placed over a black backing and for paint/varnish over white backing. The formula for calculating opacity from [4] is

$$\text{Contrast Ratio} = \frac{Y_{ob}}{Y_{ow}}, \tag{2}$$

where Y_{ob} and Y_{os} are Y tristimulus values for paint/varnish over black and for paint/varnish over white, respectively. A method is also standardised by ISO as a method to determine the opacity of paper [5]: The contrast ratio between measurement are made for one sheet of paper with a black cavity as backing, and of a pad of material thick enough to be opaque. The method stanradrised in [4] and [5] are designed for thicker materials than ink (paint/varnish films are between 25-75 microns thick, whereas ink films are between 1-3 microns). It is therefore reasonable to assume there could be a more accurate method to predict perceived opacity of ink. The need for a new model for ink opacity, that correlates better with the visual perception of opacity, has been proposed by [6].

This paper aims to investigate potential candidate methods for an ink opacity metric. The scope is limited to include only white ink, which has an important application as it is used as a coating layer. White ink is applied on non-white substrates as an underprint layer before printing the actual image, to increase the colour gamut; and it is applied as an overprint layer when an image is printed onto transparent substrates, either to diffuse back light or to permit printing on the reverse side [8]. Samples were made by printing white ink onto white, transparent and kraft paper substrates. These were used to collect subjective data on visual appearance of opacity in a psychophysical experiment. The data were used to evaluate the established contrast ratio together with other proposed methods involving the relative CIE lightness, the spot colour tone value (SCTV), colour difference, colorimetric density.

Experiment

An experiment was set up to collect subjective data on visual opacity of white ink. Ink samples were made, and 27 observers were asked to do a magnitude estimation of the samples' ink opacity. The selection of observer included both expert (14) and naive (13) observers, and males (17) and females (10). The average observer age were 32, and the overall age range is 11 to 78 years.

Samples

Samples were made by printing strips of white ink, with different ink film thickness (IFT), onto substrates. The prints were made by IGT Testing Systems with a C1-5 IGT printability tester, with a rubber printing disc. The three substrates that were used in the experiment are the standard Laneta test substrate defined in ISO 2846-1:2017 (referred ton here as CT2846), clear Melinex and kraft paper. 9 variations of IFT were printed onto the three substrate types (27 samples in total). The CT2846 substrates include a printed black region, which the white ink is printed on top of. The mounting of the CT2846 samples are illustrated in figure 1. The IFT on the CT2846 varied from 0.1μm to 5.7μm. The clear Melinex samples were mounted onto a sheet of white paper with a printed black strip across, which is illustrated in figure 2.

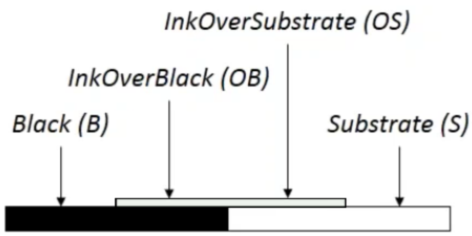

Figure 1. *Mounting of samples on CT2846 substrate.*

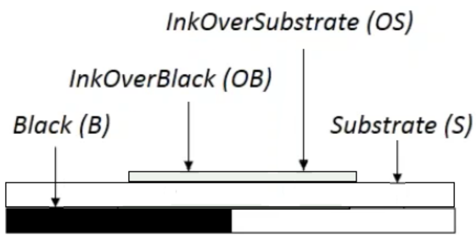

Figure 2. *Mounting of samples on clear Melinex substrates.*

The IFT on the clear Melinex varied from 1.0μm to 15.5μm. Because the kraft paper differs in appearance from the white ink, it was not considered necessary to include a black region to make opacity differences visible, and ink is printed directly onto the kraft paper. The IFT on kraft paper varied from 1.2μm to 10.4μm. One sample from each substrate set is shown in figure 3.

Measurement of samples

Measurements were made by GMG GmbH & Co. Data for each sample were obtained with spectrophotometers with different measuring geometry: i1Pro 2 (0:45), and CM-2600D with and without specular component included (di:8 and de:8, respectively). M0 measurements from the i1Pro2 were used. XYZ and CIELAB values were calculated using the CIE 1931 (2 degree) observer and D50 illuminant. Four areas of the samples were measured: substrate (S), ink over substrate (OS), black (B) and ink over black (OB). The ink samples on kraft paper had only two measurement areas available, S and OS. To account for potential non-uniformity of the ink coatings, measurements were repeated (three measurements for OB and four measurements for OS) and averaged. i1Pro2 measurements of the relevant regions of selected samples are given in table 1.

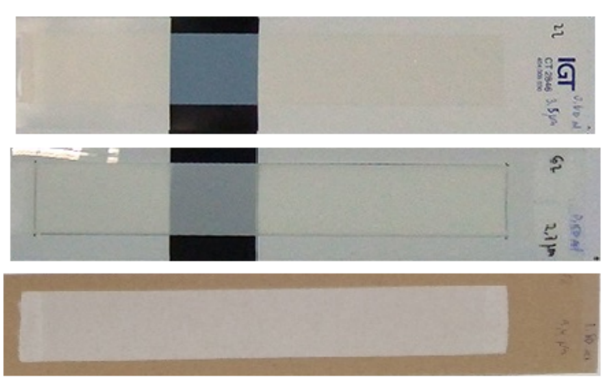

Figure 3. *From top: White CT2846 substrate with a black strip and coated with white ink, clear Melinex coated with white ink and mounted onto white paper with a black strip, and kraft paper coated with white ink.*

CIE Lab values measured with i1Pro2 for the substrates, the black area, and ink over black for three samples: Sample with the highest (H), the middle (M), and the lowest (L) opacity levels for CT2846, clear Melinex and kraft paper substrates.

CT2846			
	L	a	b
Substrate	96.68	-0.33	3.67
Over black H	76.80	-4.84	-7.30
Over black M	63.70	-5.27	-11.72
Over black L	15.32	-0.99	-3.83
Black	6.65	-0.82	-2.61
Clear Melinex			
	L	a	b
Substrate	93.48	-0.99	-1.20
Over black H	89.72	-2.53	2.43
Over black M	85.24	-2.768	-0.80
Over black L	0.88	-4.61	-7.49
Black	8.48	0.63	-3.21
Kraft Paper			
	L	a	b
Over Substrate H	79.24	1.06	4.12
Over Substrate M	72.48	3.12	8.21
Over Substrate L	69.49	4.28	11.37
Substrate	63.87	6.51	19.09

Experimental set up

The experimental set up is shown in figure 4. The samples were presented manually in the viewing booth (with D50-simulating illumination at 2490 lux) one by one, in a randomised sequence. As shown in figure 5, a mid-grey paper with an approximately 30×40 mm large window was used to mask the sample so that only the relevant area was visible: Ink over black was visible on the CT2846 and clear Melinex substrates, while ink over the substrate was visible for the kraft paper substrate. Visual anchors were attached in the window: White ink over a white CT2846 substrate were presented as the visual anchor for fully opaque ink, and the substrate itself were presented as fully transparent ink. Figure 5 shows the window that isolates a sample of white ink printed on the CT2846 substrate, and the corresponding visual anchors for 0 and 100% opacity. A magnet (covered by mid-grey paper) was used during the experiment to fix the samples to the back wall of the viewing booth. The motivation for doing this was to limit the amount of scattering between the layer of the clear Melinex substrate and the backing, as these were not in optical contact.

The observers were sitting at an approximate distance of $0,5$m away from the viewing booth in a dark room. The observers were instructed to estimate the opacity of the isolated ink on a scale from 0 (transparent) to 100 (opaque). The samples on different substrates were presented in a random order. Three non-random selected samples were presented in the beginning of

Figure 4. *Experimental set-up in lit room: Viewing booth with a sample placed inside, held in place by a magnet, and a chair placed in front of the table for the observers to sit.*

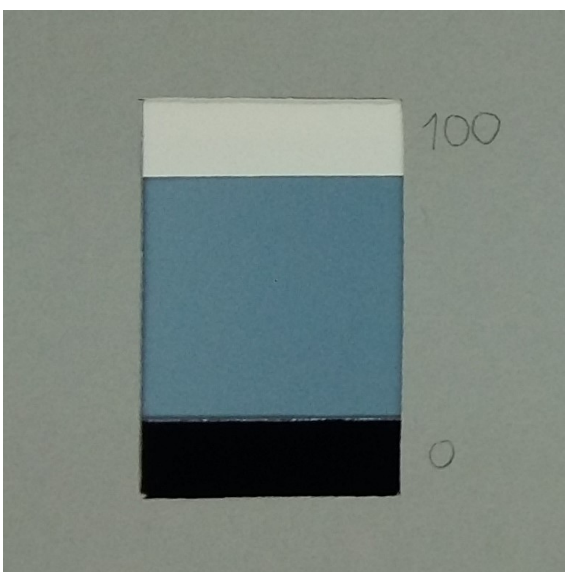

Figure 5. *Window isolating a sample of white ink printed over black on CT2846 substrate. Visual anchors show the black backing (0 opacity) and fully transparent ink (100 opacity).*

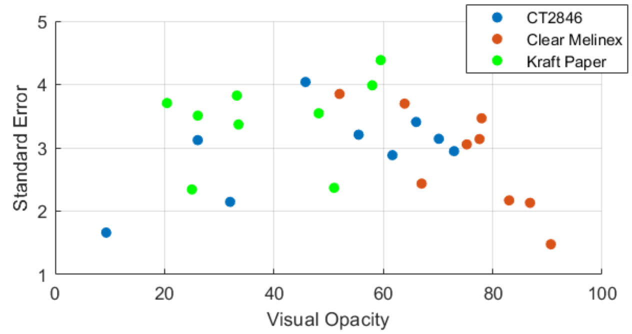

Figure 6. *Plot of inter-observer standard error of ink samples against average visual opacity.*

Main visual opacity (O_v) and standard error (SE) for the white ink sample on CT2846, clear Melinex and kraft paper substrate, obtained from psychophysical experiment

CT2846									
ID_s	142	149	158	19	16	22	32	36	42
O_v	9	26	32	46	55	62	66	70	70
SE	2	3	2	4	3	3	3	3	3
Clear Melinex									
ID_s	201	62	77	206	208	209	211	213	215
O_v	52	64	67	75	78	78	83	87	91
SE	4	4	2	3	3	3	2	2	1
Kraft Paper									
ID_s	165	166	167	168	169	170	171	172	173
O_v	20	26	25	34	33	48	51	58	60
SE	4	4	2	3	4	4	2	4	4

the experiment with low, mid and high levels of opacity, to allow observers to self-calibrate. The visual opacities for these three calibration samples were not included in the analysis.

Results

The experiment revealed that the visual opacity of the samples set on CT2846, clear Melinex and kraft paper have a range of 9-73 %, 52-91 % and 20-60 % opacity, respectively. The mean visual opacity scores and the inter-observer standard error (SE) of the ink samples are given in table 2. The SE between observers are plotted against visual opacity (O_v) in figure 6. The plot shows that the observers were most uncertain about the opacity of the samples in the mid-range of opacity. One-way ANOVA F-test were conducted in Minitab for the 27 observations for each of the 27 samples. Adjusted mean squares (MS) for the samples were obtained with 8 degrees of freedom (DF), while adjusted MS of the error were obtained with 288 DF. The F-values for ink on CT2846, clear Melinex and kraft paper are 55.6, 16.37 and 20.52, respectively, which are great enough to reject the null hypothesis for all significance levels (the critical value for a 0.05 significance level for 8 and 288 DF is 1.97). Thereby, we can conclude that there are samples that have significantly different perceived opacity.

Analysis

Five candidate methods for calculating opacity of ink from physical measurements were evaluated. The methods were tested as correlates for a linear regression of the visual data.

Candidate Metrics

The five candidate metrics were:

- The contrast ratio
- The relative CIE lightness (L*)
- Spot colour tone value (SCTV)
- Colorimetric density
- Colour difference

Contrast Ratio

As mentioned, the contrast ratio of ink over black and ink over substrate is the standard method for calculating hiding power of paint and varnish, and opacity of paper. We used the formula is given in equation 2 as a correlate for ink om CT2846 and clear Melinex, and a variation, Y_{os}/Y_s, as a correlate for visual opacity for ink on kraft paper.

Relative Lightness

A ratio that includes the difference of L^* for ink over black and ink over substrate is proposed:

$$\text{Relative } L^* = \frac{L^*_{os} - L^*_{ob}}{L^*_{os}}, \tag{3}$$

where L^*_{os} is the CIE lightness of ink printed over substrate, and $L*_{os}$ is CIE lightness of ink printed over black. The variation used on ink on kraft paper was $(L^*_s - L^*_{ob})/L^*_s$.

SCTV

The calculation of SVCT are standardised in [1]. The equations for SCTV is

$$\text{sctv} = \sqrt{\frac{(V_{xs} - V_{xos})^2 + (Vys - V_{yos})^2 + (V_{zs} - V_{zos})^2}{(V_{xs} - V_{xob})^2 + (Vys - V_{yob})^2 + (V_{zs} - V_{zob})^2}}, \tag{4}$$

where s denotes measurements of the substrate, os denotes measurements of ink over substrate, ob denotes measurements over black. The V components are given by $V_x = L^* + (116a)/500$, $V_y = L^*$ and $V_z = L^* - (116b)/200$, where a and b are the CIE a and CIE b values, respectively. This method was not used for the kraft paper, because three different measurement points were required.

Colorimetric Density

The proposed colorimetric density is given by

$$\text{DE} = \log(\frac{Y_s}{Y_{os}}), \tag{5}$$

where Y_s and Y_{os} are Y tristimulus values for the substrate and for ink over substrate, respectively.

Colour Difference

For the last candidate method, the colour difference, the $\Delta E2000$ formula were used to calculate the colour difference between ink over black and ink over substrate, ΔE(ob,os), for samples on CT2846 and Clear Melinex. For samples on kraft paper, the variation ΔE(os,s) were used.

Linear Regression

Linear least squares regression was performed using Matlab's curve fitting tool. The results were good for all proposed metrics, ie. there were strong correlations between the visual opacity and the proposed correlates. A simple form for ink opacity metric is considered preferable, and thus linear regression were considered even though a second-order regression provides a better fit for some of the correlates. Scatter plots of visual opacity vs. the proposed correlates for ink on CT2846 and clear Melinex are shown in figure 7. Equivalent plots for ink on kraft paper, with the variation of the correlates, appear to closely approximate a linear correlation, and are not included in the figure. The plots in figure 7 show that there is a shift between the samples on CT2846 and clear Melinex for most candidate methods. The measurement methods for these substrates are the same, but a possible cause of this shift is the different mounting processes for the substrates; the layers without optical contact might cause more scattering in the samples on clear Melinex. The scatter plot of visual opacity vs. the correlates for ink on kraft paper are on a different scale than ink on the other two substrates, due to the different methods used to print the samples.

R^2-values and the coefficient of variation (CV) were used to evaluate the performance of the linear models. The formula for CV used for the analysis are

$$\text{CV} = 100\frac{\sqrt{(1/n)\Sigma_{i=1}^n (P_i - V_i)^2}}{(1/n)\Sigma_{i=1}^n V_i}, \tag{6}$$

where n is the number of samples, P_i is the model prediction, and V_i is the visual result [10]. CV is the percentage of disagreement between the model prediction and experimental visual results. The R^2 and the CV values for the proposed correlates are shown in table 3 for each substrate type separately.

The correlates based on ink over substrate measurements (kraft paper) show a better overall correlation than the correlates based on ink over black measurements (CT2846 and clear Melinex). A reasonable assumption is that this will only be the case when the substrate deviates in visual appearance from the ink, either by colour, texture or glossiness. Another remark is that the slightly improved performance does not necessary mean that correlates based on ink over substrate provide better results than correlates based on ink over black; the strong overall correlations could also arise because the kraft paper samples has the smallest range of visual opacity, ie. this sample set does not include potentially problematic extreme values. We can also see on the performance values that the correlation is overall better for samples on clear Melinex than for ink on CT2846, but this is likely because the clear Melinex sample set does not include samples with low visual opacity values.

Figure 7 show that the SCTV correlate has a curved shape, and the performance values for the samples on CT2846 (which include low-range visual opacity values) shows that this method is less suited for a linear model. This method does also have the disadvantage of not being applicable for ink on substrates without a black region. The colorimetric density correlate does not produce coinciding results for CT2846 and clear malinex samples, and are the second poorest and poorest correlate for these substrates, respectively.

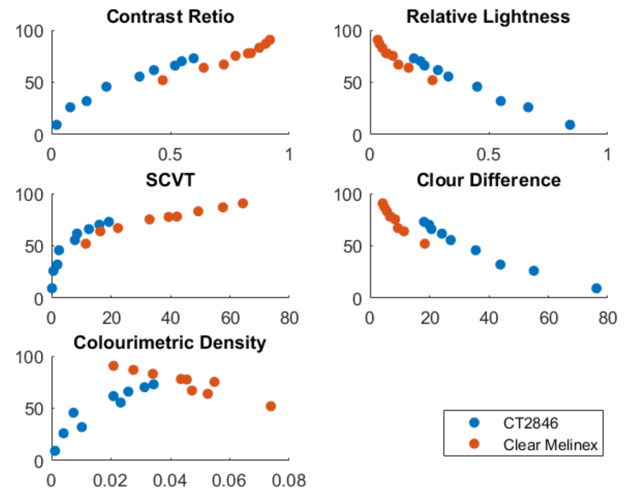

Figure 7. *Scatter plot of visual opacity for the proposed correlates for ink on CT2846 and clear Melinex.*

The best prediction of the visual data for the samples on CT2846 with 3.67 % disagreement is the relative L* correlate. The contrast ratio is the best correlate for samples on the clear substrate, with 2.97 % disagreement. For kraft paper, and the ink over substrate correlates, the colour difference method has the least disagreement by 3.64 %. These methods are all practical and promising candidates for an ink opacity metric. The colour difference method is possibly the most practical correlate, as it will account for colour in both substrate and ink coating.

Conclusions

A psychophysical scaling experiment was conducted with samples of translucent white ink on CT2846, clear Melinex and kraft paper substrates. Visual data were collected from 27 observers for nine samples on each of the three substrates. Based on ANOVA analysis we conclude that there were significant difference of visual opacity among our samples.

The proposed methods to calculate correlates for the visual data provide good fits in linear regression. Based on the performance of the linear models we do not consider SCTV or colorimetric density to be good candidates for a visual opacity metric for ink. Contrast ratio, relative L^* and colour difference provide more promising results. Neither of the other candidates are obviously superior to the contrast ratio, which is the widely-used method for measuring opacity for paint and varnish coatings and paper. On the basis of these results, there are advantages to each of the methods, and more work is needed to evaluate candidate metrics for coloured inks, and for visual opacity of ink where there is no black printed region. A future extension to this evaluation of potential candidate metrics is to obtain visual observations using coloured inks and possibly with different substrates, for example coloured and metallics.

Acknowledgements

We would like to acknowledge IGT Testing Systems for providing the ink samples used in this experiment, and GMG GmbH & Co for making the measurements.

Results of psychophysical experiment for white ink on CT2846, clear Melinex and kraft paper substrate.

CT2846		
Method	R^2	CV
Contrast Ratio	0.9609	8.44
Relative L*	0.9926	3.67
SCTV	0.8176	18.23
Colour Difference	0.9628	8.23
Colouri. Density	0.8843	14.52
Clear Melinex		
Method	R^2	CV
Contrast Ratio	0.9623	2.97
Relative L*	0.9388	3.78
SCTV	0.9452	3.58
Colour Difference	0.9300	4.04
Colouri. Density	0.8764	5.37
Kraft Paper		
Method	R^2	CV
Contrast Ratio	0.9819	4.79
Relative L*	0.9852	4.34
SCTV	-	-
Colour Difference	0.9896	3.64
Colouri. Density	0.9864	4.16

References

[1] ISO 20654:2017(E), Graphic technology - Measurement and calculation of spot colour tone value, International Organisation for Standardisation (2017).

[2] ISO/DIS 13655.2:2016, Graphic technology - Spectral measurement and colorimetric computation for graphical art images (2016).

[3] ISO 6504-1:1983, Paints and varnishes – Determination of hiding power – Part 1: Kubelka-Munk method for white and light-coloured paints (1983).

[4] ISO 6504-3:2006, Paints and varnishes – Determination of hiding power – Part 3: Determination of contrast ratio of light-coloured paints at a fixed spreading rate (2006).

[5] ISO 2471:2008, Paper and board - Determination of opacity (paper backing) - Diffuse reflectance method, International Organisation for Standardisation (2008).

[6] ISO/TC 130/WG 3 N1865, A standard for ink opacity - justification (2016).

[7] Kiran Deshpande, Phil Green, Phil and Michael R Pointer, Characterisation of the n-colour printing process using the spot colour overprint model, Optical Society of America, Optics express 26, pg. 31786–31800. (2014)

[8] Johanna Kleinmann, Process control and colour management of white ink in inkjet printing, MSc Thesis, London College of Communication (2008).

[9] Roy S Berns and others, Billmeyer and Saltzman's principles of color technology, Wiley New York, 2000, pg. 7-9.

[10] Changjun Li, Zhiqiang Li, Zhifeng Wang, Yang Xu, Ronnier Ming Luo, Guihua Cui, Manuel Melgosa, Michael H Brill, and Michael Pointer, Comprehensive color solutions: CAM16, CAT16, and CAM16-UCS, Wiley Online Library, Color Research & Application, 6, 703–718 (2017)

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Helene B. Midtfjord received her M.Sc. in physics from the Norwegian University of Life Sciences (2017). Since then she has done research as a Ph.D candidate at the Norwegian University for Science and Technology in Gjøvik, Norway. Her work has focused on visual appearance of materials.