**Gloss and Goniocolorimetry of Printed Materials**

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**Abstract:** Angular distribution of reflectance spectra and of colorimetric parameters for printed papers (varnished and not) and foils, clear and metallized, were measured by goniospectrophotometry, with a photomultiplier for visible region, or a spectrophotometer as a detector, keeping the light source in a fixed position, $−45°$ anomalously. All reflectance spectra were related to near-Lambertian BaSO$_4$ powder white standard, relative to which the color coordinates were calculated. The photometric cosine law holds for an ideal diffuser; consequently, all color parameters are significantly perturbed by gloss in a large region, several $10's$ of degrees around the specular angle. The reflectance peak in the specular angle region of glossy material can be well approximated by the Lorentz function, especially in the vicinity of the specular angle. Lightness, chroma, and hue angle in the gloss angle region suffer as a result of high changes and extremes depending on the gloss of the material tested. This is what complicates color measurements and full determination or definition of the complex appearance of printed materials. The change of chroma with varnishing of glossless materials was clearly elucidated. It was found that “bottom color gloss” considerably influences the appearance of printed metallized foils or other prints on high glossy substrates. © 2003 Wiley Periodicals, Inc. Col Res Appl, 28, 335–342, 2003; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/col.10177

**Key words:** gloss; color; appearance; gonio; multiangle colorimetry; foil; paper

**INTRODUCTION**

It is well known that the gloss of printed materials has a significant effect not only on appearance but also on perceived color. Matte layers appear less intensively colored, with lower chroma and higher lightness than the corresponding glossy layers (after varnishing, or wet ink before drying). Generally, geometric attributes of a surface influence perceived and measured chromatic parameters in the chosen particular geometry. It is a question whether the influence of gloss is sufficiently suppressed or not measuring colorimetric parameters in standard geometries, or whether it is possible to separate fully geometric attributes of appearance and color ones. Another question is how an objective and real complex appearance can be defined and determined, considering perception by two human eyes at two different angles, simultaneous multiangle exposition from a nonpointed, large-area source of light. Moreover, the gloss measurement alone includes some problems as a result of extremely high spatial resolution of the retina of a single eye relative to used apertures and geometry. The standards and their terminology are open to interpretation, and weak correlation exists between manufacturers’ devices, especially on textured surfaces. So the gloss effect on appearance is less understood than other factors, such as color.

It is obvious that the complex appearance of a material surface can be better elucidated and defined by multigoniophotometry or goniocolorimetry. Several authors have attempted to solve the problem using spectrophotometry or colorimetry at more than one angle. Some vendors offer goniophotometers or multigoniometer that can measure several detection angles, commonly four or five. The chosen angles (measured against the normal to the surface) are usually $\theta = 30°, 20°, 0°, −30°$, and $−65°$, keeping the incident light at $−45°$. In aspecular interpretation (measured against the specular position) the angles are $\alpha = 15°, 25°, 45°, 75°$, and $110°$ ($\alpha = \theta_{spec} − \theta$, light source at $\alpha = 90°$). But such multangle...
We obtained the angle-resolved color data from spectral remission measurements using mainly Spectrolino as a spectral reflection detector placed in the goniometric arm (Fig. 1). We used the measured remission spectra in the Spectrolino emission mode to calculate the color coordinates, lightness, chroma, and hue angle \((L^*, C^*, h^*)\) of samples and of a white standard (BaSO\(_4\) powder), using the well-known and common procedure\(^6\) in the program MATLAB. The spectral range used by Spectrolino was 380–730 nm, with the step of 10 nm, an observer of 2°, and no filter.

The color coordinates could be obtained also by PMT measurements, with the same calculating procedure. However, it is too laborious and time-consuming because of the time it takes to scan the samples and the white standard at every angular position. The PMT technique is ideal for angular-resolved remittance measurements at constant wavelength, which would be difficult to manage with Spectrolino.

The colorimetric results in the position \(\theta = 0^\circ\) were compared with the classical measurement by Spectrolino in its standard geometry 45/0, in common absorption mode, with the illumination of D65 by internal light source.

The samples, cyan printed carton (Aukocart 220 g/m\(^2\)), cyan ink Rapida F 7000, free of varnish and with several varnishes:

UV high-gloss varnish (Huber Glanzlack 40Y000119)—UV Printing high-gloss varnish (Huber Hochglanz 9500)—PH Dispersion matt varnish (Huber Acrylac matt 600/50)—DM and reversally (back) printed polypropylene (PP) foils (biaxially oriented, 20 \(\mu\)m), clear and metallized by aluminum (Al) after the ink print over the ink layer of cyan (Gebruder Schmidt for gravure printing), were measured on the black and, in some cases, also the white background substrate. The choice of the measuring background is crucial mainly in the case of nonmetallized foils without an overcoating (covering) white ink layer. Remission and color parameters of reversally printed and metallized foils are measured through the transparent PP layer.

All measured reflectance spectra were related to the spectra of the near-Lambertian BaSO\(_4\) white standard in the form of a pressed powder\(^10\) to obtain relative reflectance against the white standard

\[
R/R_w = I_r(\theta, \lambda)/I_r(\theta, \lambda) \quad (1)
\]

or to the aluminum mirror reflection in the specular angle (alias \(I_s\)) to get near absolute reflectance, considering nonidealities of the mirror:

\[
R = I_r(\theta, \lambda)/I_s(\lambda) = I_r(\theta, \lambda)/I_{mirror}(\theta_s, \lambda) \quad (2)
\]

where \(I_r\) is reflected light intensity, \(\lambda\) is wavelength, and \(\theta_s\) is the anormal specular angle.

It is evident that the relative reflectance \(R/R_w\) of glossy samples can greatly exceed the value of 1 in the specular angle region. The relative values are very useful, because this eliminates the spectral dependence of the light source.
emissivity and the detector sensitivity. Moreover, the general cosine law in angular dependence of reflectance is eliminated, and some possible systematic error of the measurement can be suppressed. However, a small error connected with the nonideality of the diffuse white standard can appear.

So the angular dependence of the values of \( R \) is distinguished from the angular dependence of \( R/R_{st} \), basically by the presence of general cosine law dependence (Figs. 2 and 3), because the standard also follows the cosine law. The deviation of the diffusion BaSO\(_4\) standard from the cosine law is limited (Fig. 2). The deviations of remission of varnished cyan printed cartons from the remission of the BaSO\(_4\) powder (Fig. 3) sharply increase around the specular angle region (\( \theta = 45^\circ \)), and some deviations are noticeable at very shallow angles, larger than \( 60^\circ \). Some asymmetry of the gloss reflection peak can be observed. The remission of well-diffusing surfaces ought to be a constant, parallel to the diffuse standard line.

It is obvious that the obtained shape of the reflection peak depends on the values of illumination and detection beam spread (apertures) used in the measurement (the divergence of incident beam and the aperture angle of detector). The detail geometry used in all presented measurements is described in Table I as “normal” values. Another different geometry with narrower apertures (“narrow” in Table I) was used just in few cases (only in Fig. 4) to demonstrate the aperture effect on the measured parameters. Both geometries are narrower than those recommended and acceptable by the International Commission on Illumination (CIE 15.2., ASTM E 1164-94).\(^{11}\)

The “normal” geometry is easy to achieve and was used also in all goniocolor measurements, with Spectrolino as the spectral reflection detector.

The aperture effect is, of course, stronger with glossy surfaces that have sharper reflection characteristics. Wide apertures enlarge the measured gloss angle region, more for glossy samples than for matte ones (Fig. 4). It seems the apertures for multangle measurements ought to be narrower and more strictly defined than apertures for single-angle standard geometries. In this context, it is useful to consider the angle conditions in a situation of perception and appreciation by two human eyes: two angles, small detection apertures, but large illumination apertures (diffusion multangle illumination from large-area sources). In such a case, the geometric angle region of gloss effect is considerably enlarged, so the perception of color and gloss is greatly influenced.

The succeeding results presented are obtained at “normal” aperture conditions.

RESULTS AND DISCUSSION

Gonioreflectance Measurements

All measured angle-resolved remission characteristics contain a peak in the specular angle region (Figs. 2 through 4) more or less high and spread, depending on the gloss level of measured material. This gloss intensity peak can be described mathematically in several ways. The angular dependence of remitted light intensity can be divided into two components: the scattering (\( F \)) and the gloss (\( G \)).

\[
R(\theta)/\cos\theta \sim I_\alpha(\theta)/I_\alpha,\cos(\theta) = R(\theta)/R_{st}(\theta) = F + G f(\theta) \tag{3}
\]

\( F \) increases with surface roughness up to values near 1. On the other hand, \( G \) increases with gloss and reflectivity of the surface to high values, followed by a thinning of the angle region of gloss performance defined by a symmetrical function \( f \) of the aspecular angle. Gardner et al.\(^{12}\) have proposed for newsprints the use of a power of \( \cos\theta \), by analogy to the Lambertian distribution,

\[
f = \cos^n(\theta - \theta_{sp}) \tag{4}
\]

The same fits were used by Seymour\(^{11}\) for a black-colored paper. For nonglossy papers, the exponent \( n \) is not.
TABLE I. Used geometries in goniophotometric measurements, normal, narrow, and CIE maximum acceptable values in geometry of 45/0.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Goniomeasurements</th>
<th>Goniomeasurements</th>
<th>CIE geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>“Normal”</td>
<td>“Narrow”</td>
<td>Maximum values</td>
</tr>
<tr>
<td>Illumination axis deflection</td>
<td>45° ± 1°</td>
<td>45° ± 1°</td>
<td>45° ± 2°</td>
</tr>
<tr>
<td>Illumination aperture</td>
<td>2°</td>
<td>2°</td>
<td>16°</td>
</tr>
<tr>
<td>Width of illuminated part of sample</td>
<td>3 mm</td>
<td>1 mm</td>
<td></td>
</tr>
<tr>
<td>Detection axis deflection</td>
<td>θ ± 1°</td>
<td>θ ± 1°</td>
<td>0° ± 10°</td>
</tr>
<tr>
<td>Detection aperture</td>
<td>10°</td>
<td>4°</td>
<td>16°</td>
</tr>
</tbody>
</table>

too high, but in the case of reflection from a common ink, $n$ overcrosses the value of 70. For high-gloss prints on foils and varnished paper prints, the exponent $n$ is much higher than 100. In the case of printed foils, it is more than 300 (Fig. 5, Table II) or much higher, depending also on chosen aperture. Such a high-value exponent is not mathematically comfortable and is unacceptable from the viewpoint of problematic physical interpretation. It is physically reasonable to use error functions because of the statistical character of a smoothness and gloss perturbation. The fits of printed foil and paper data by Gaussian ($f_G$) and Lorentzian ($f_L$) error functions are illustrated in Fig. 5:

\[
f_G = \exp\left(-2(\theta - \theta_p)^2/(w_G)^2\right)
\]

\[
f_L = \left[1 + 4(\theta - \theta_p)^2/(w_L)^2\right]^{-1}
\]  

where $w_L$ and $1.18 \ w_G$ are the full halfwidths of the gloss component peak representing directly the effective angle region of gloss performance. The Gauss fits give practically the same curves as the cosine fits, and both have the large deviation at the peak maximum and near the peak base. It is evident that the Lorentz function fits best concerning also the far shoulders of peak distributions. Lorentz function is sharper at the top and thinner in the middle, but with a broader peak base. However, some asymmetry is present; perhaps the asymmetric Lorentz function could be better (two functions with different $w_L$ and offset $F$ for $\theta > \theta_p$ and $\theta < \theta_p$) if any artifact of asymmetry could be completely excluded. Availability of Lorentz fit with its broader peak base demonstrates that the gloss affects a considerably broad scale of angles, so it impacts measured colorimetric parameters.

The exponent $n$ increases, and both the halfwidths $w_L$ decrease after the application of ink on the paper (Table II). The amount of specular reflection increases little with the addition of ink; the specular peak is narrower and higher, with a slightly larger integral and smaller scattering component (offset $F$). This indicates that the refraction of paper and dry ink is similar, but the application of ink makes the surface smoother. The effect is more expressive after varnishing of the printed paper with the glossy varnishes.

However, in the case of foils, their high gloss decreases slightly after printing, $n$ decreases, and halfwidths increase, whereas the scattering and gloss components increase with a black background.

A metal layer under the ink on foils causes a large increase in the gloss component, whereas the halfwidth of the gloss angle region does not decrease; on the contrary, it moderately increases again. The metal layer performs as a mirror under the semitransparent ink, so the reflection from the bottom interface is present and bears the color information of the ink (a backside “bottom color gloss,” Fig. 6), contrary to the front side noncolor reflection (a “top surface white gloss”) that is white like the light source. The light reflected from the underlaid metallic (Al) layer is partially

FIG. 4. Normalized relative reflectance of cyan printed carton, nonvarnished, and UV varnished at normal (norm.) and narrow aperture conditions in the gloss angle region measured by PMT at 450 nm.

FIG. 5. Normalized reflection data of cyan printed carton and PP foil (reverse print and metallization) and their fits: cosine, Gauss and Lorentz, measured by PMT at 450 nm.
scattered, transferring backward through the ink layer, which causes the widening of the gloss component peak. The phenomenon of bottom color gloss is present also in any other print or semitransparent colored layer on a high-gloss substrate (prints on Al foils and metallized papers, ink layers on metal plates, etc.).

This bottom colored reflection contributes to a special color appearance of printed metallized foils and complicates the inspection of color and the control of a printing process. Metallic layers in prints cause not only the gloss and appearance changes, which is their proper goal, but also color changes represented by hue shifts. The color shifts due to metallic layer application are often an unacceptable color difference $\Delta E^*$, and it is not easy to guess these shifts in the prepress process. The influence of the bottom color gloss on the color parameters is discussed later, when we consider the chroma of printed foils.

The portion of the bottom color gloss can be demonstrated well by comparing the reflected light distribution from the reversally printed foil, nonmetallized and metallized (after print). The portion can be calculated by subtracting one from the other (Fig. 7).

**Goniocolor Measurements**

From the above, it is evident that gloss or scatter affects the appearance and color perception of material in a rather wide range of viewing angles. To evaluate this effect, the color parameters were calculated from remission spectral data measured at various detection angles by the Spectrolino spectrophotometer in emission mode setting. In this mode, the Spec-
trolino has recorded angle-resolved remission spectra from samples, illuminated by external incandescent halogen lamp at a fixed position of $\theta = -45^\circ$ (Fig. 1). The calculated colorimetric coordinates $L^*, C_{ab}^*, h_{ab}$ of the cyan printed carton nonvarnished and varnished with various varnishes as a function of detection angle are illustrated in Figs. 8 through 10.

As expected, the lightness exhibits increasing peak, with a gloss level in the specular angle region (the highest for the UV varnish and the lowest for the matte one, Fig. 8). It exceeds the common limit of 100 considerably, which is a consequence of the diffuse white standard (with near-zero gloss component) used in the color coordinates calculations. (If some glossy reference white were used, the lightness limit of 100 need not be exceeded.) Far from the specular region, the lightness is rather stable and independent of the varnish type used. A little higher value for nonvarnished print is caused by higher optical scatter from the diffuse surface. However some asymmetry is reproducibly present at angles above $70^\circ$, especially for the matte surface.

More interesting is the performance of the chroma in angular resolution (Fig. 9). It strongly decreases in a wide specular region of angles ($\pm 15^\circ$), depending on the surface gloss. For a UV-varnished printed carton, the specular angle chroma reaches nearly zero, because the light source reflection from the high-gloss surface dominates the diffuse light colored by the printed layer at this angle. However, at a large angle away from the sharp specular region, the chroma of the more glossy sample (UV-varnished) is higher than that of less glossy ones. This phenomenon is well known by printers as the increase of chroma with the varnishing, considering the perception outside the specular angle region, as well as the measurement in standard geometry 45/0. The human perception of printed matter is commonly more complex and integral (multangle): diffuse illumination from flat light sources, two eyes (two viewing angles), but excluding the light source reflection. The chroma of glossy prints is really higher at any angle excluding the narrow specular angle region, with the biggest difference just near the excluded region. Printing varnish was the exception; probably, it was a little tinted.

A similar change of chroma has been observed during the drying process of prints. The chroma, as well as the density of wet printing ink, decreases after drying by more than 5% (in some cases, up to 20%), depending on the gloss of the finished dry ink surface. The white light scattered from the top surface of the rough layer (dry ink or matte varnish) decreases the chroma. This scattered white light is less for a wet ink surface, or after applying high-gloss varnish, and is collected at the specular angle reflection, so the chroma at nonspecular angles will be higher.

Of great interest is the performance of the hue angle (Fig. 10), where the matte varnished sample undergoes the least changes, whereas the high-gloss varnish has a sharp single peak, and nonvarnished ink has a double peak. The peaks point to lower hue angles (cyan is changing toward yellow near the specular angle). This is in agreement with the color temperature and color tone of the incandescent light source that is probably not fully compensated by normalization against the BaSO$_4$ at these extreme specular conditions.
Moreover, the hue angle of near white light with a low chroma reflected at the specular position is ill-conditioned (has a big error). The effect is reduced (but present) in the $a^*b^*$ plane. A surprising fact is the small but repeated increase of hue angles in a tight vicinity of the peak.

In the case of transparent printed foils, the measured color coordinates significantly depend on the chosen measuring background substrate, black or white. This dependence vanishes when the ink layer is undercoated by a metal layer or white covering layer, which is often used. Color parameters $L^*, C_{ab}^*, h_{ab}$ at different detection angles were found for reverse (back) printed PP foils by cyan ink (Figs. 11 through 13) in the gravure printing technique, nonmetallized and metallized, measuring reflectance spectra by Spectrolino in emission mode placed in the goniometric arm (Fig. 1).

A typical specular reflection peak of lightness (Fig. 11) from the glossy top surface of PP foil is amplified and widened in the case of metallized foil by the bottom (back) reflection from the specular metal ink interface (Fig. 6). So the large region of angle distribution of color parameters is influenced by the gloss. The shapes of lightness distributions are similar, namely, for the metallized and the black background cases. In the case of a white background, the value of $L^*$ at far aspecular angles is two times higher because of intense scatter from the underlying diffuse white substrate. Consequently, the specular peak is lower at the white background than that of the metallized foil. The peaks of nonmetallized foils at both backgrounds are similar, because the top surface reflection does not depend on a background.

The shapes of detection angle distribution of the chroma are very expressive (Fig. 12). The reverse peaks can be found in the gloss angle region. In accordance with expectations, the chroma of nonmetallized foils decreases in the specular angle region because of the presence of the white light source reflected from the top surface. However, the chroma of metallized foil increases considerably, because the intensity of colored light reflected from the metal surface under the ink layer (Fig. 6) is higher than the intensity of white light reflected from the top surface of the printed sample. The bottom color gloss effect is manifested here very clearly and unambiguously. This outstanding behavior of chroma has a major effect on the special appearance of colored prints on metallized substrates. The shapes of chroma in the far aspecular region are standard, analogous to those of lightness. A white background causes higher values of chroma and lightness, whereas the metallic underlayer acts as a black background in this diffuse light angle region. However, the influence of gloss extends to high values of aspecular angles, $\sim 30^\circ$ (from $15^\circ$ to $75^\circ$ anomalously in this case).

The large extent of gloss effect on color is confirmed also by the hue angle behavior (Fig. 13), especially in the case of metallized foils. Cyan is changing toward green and yellow-green in the specular angle region, depending on the amount of mirror-reflected light and its color. It is caused probably by a better reflection of light with longer wavelengths, and
with the color temperature of the incident white light, which contains a large portion of yellow and red. (Also, the hue angle of near-white light reflected at the specular position is ill-conditioned.) The hue angle is shifted markedly to warmer colors also outside the specular region at the white background measurement and partially also at the measurement of the metallized foil. The shifts were confirmed at \( \theta = 0^\circ \) by the classical measurement in 45/0 geometry. The hue values outside the specular region are not as stable as those in the carton measurements (Fig. 10). The interpretation of the hue angle shifts is not easy. It could relate to a tint of the white substrate, transparency of the PP layer and ink vehicle, and higher reflectivity of the metallic layer for longer wavelengths. The effect of light source color is compensated for principally in calculations of color coordinates by comparing the sample measurements with the real white standard measurement. However, the high volume of longer wavelengths in the incandescent light and the nonideality of the white standard may play some role.

We tested the correctness of all goniocolorimetric measurements by comparing the results (the values of color parameters \( L^*, C_{ab}^*, h_{ab} \)) at the angle \( \theta = 0^\circ \) with the values obtained by standard measurement by Spectroline as the spectrophotometer in its standard geometry 45/0. The differences were not larger than 5% in any case. The angle-resolved color measurements were carried out also by PMT detector in connection with the monochromator. The results were very similar to those obtained by the goni-Spectroline arrangement; however, the measurements were too laborious and time-consuming, with greater difference against the standard measurement at the point \( \theta = 0^\circ \). Longtime spectral scanning of the sample and of the diffusion standard at every angular position caused a larger error in the PMT color measurements.

The narrower apertures give sharper and sometimes more complicated extremes of the angle distribution of color coordinates (a double-reverse peak of the chroma maximum of metallized foils, etc.). However, the goniomeasurements with very narrow apertures are demanding and hardly applicable in practice.

**CONCLUSIONS**

We tested the effect of gloss on color by measuring angular distribution of reflectance spectra and of colorimetric parameters of printed papers and foils illuminated from a fixed angle (\( -45^\circ \) anomalously). The measurements were related to the spectra of near-Lambertian BaSO\(_4\) powder white standard. The commercial spectrophotometer GretagMacbeth Spectroline was successfully used as the spectral reflection detector for multiangle goniomeasurements.

The photometric cosine law is significantly perturbed by gloss in a considerably large region, many 10’s of degrees around the specular angle, depending on the gloss level. The reflectance peak is created in the specular angle region, where the lightness, chroma, and hue angle rapidly change and reach large extremes. The peaks are lower and much broader in matte and less glossy materials (nonvarnished printed paper) than in glossy ones (foils, varnished paper, etc.), where the peaks are narrow and high, depending on illumination and detection apertures. These large deviations from the cosine law complicate color measurements and full determination or definition of the complex appearance of printed materials compared with the perception by two human eyes at common illumination conditions. The shoulders of the peaks are rather broad in any case, so the Lorentz function seems to be the best approximation of angular distributions.

Particularly, the foil metallization enlarges the gloss peak by a colored reflection from the bottom interface, “bottom color gloss,” confirmed by chroma and lightness performance. Although the front boundary gloss is not colored and is characterized by the spectrum of the light source, the back boundary (bottom) gloss bears the color information of the ink film and essentially influences the appearance of printed metallized foils or other prints on high-gloss substrates.

Also the increase of chroma with varnishing of glossless materials, as well as the decrease of chroma with drying of prints, were clearly elucidated.