Distinctness of Image (DOI) of Inkjet Photo Papers

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Abstract

Distinctness of Image (DOI) is receiving increasing attention as an important appearance attribute that correlates with the customer's perception of "photo-like" quality in digital photography. In this paper, a new measurement technique for DOI introduced recently is applied to the evaluation of inkjet photo papers. The principle of the technique is first reviewed; and the test results for about 40 commercial inkjet photo papers are then reported. The papers are mostly of the microporous, "instant-dry" type, with 60° gloss in the range of 30-90. The printers used are an Epson R800 and an HP 5500, both with pigmented inks. The DOI results are discussed in terms of correlation with perceptual (subjective) ranking, objective quality measures such as specular gloss, and physical properties such as surface roughness. The effect of printing on DOI is also investigated in terms of the printer type, color and tint level.

Appearance and Customer Preference

The total quality of a digital photograph is a combination of its chromatic (color) and achromatic attributes (such as gloss, haze and texture), as well as its physical characteristics such as its caliper and weight. While the importance of color in the perception of photographic quality is well recognized and generally understood, the role of specular gloss is far from clear. In fact, we find that traditional gloss values often fail to predict customer preference and an emerging belief is that there may be other "gloss-like" attributes that may influence a customer's perception of photo quality. One such attribute is called Distinctness of Image, or DOI.

Distinctness of Image (DOI)

Conceptually, DOI is the sharpness or clarity of the image produced by reflection of an object on a surface. If the reflection of an object on a surface appears sharp and clear, the surface has high DOI. Conversely, if the reflection is blurry and of low contrast, the surface has low DOI. Although DOI is not a familiar term to most in the digital imaging community, it is a well known quality attribute for coatings and paints in the automotive industry. Another phenomenon closely related to DOI is "orange peel". Both DOI and orange peel are directly influenced by the texture of a surface.

To illustrate the concept of DOI, consider Fig. 1, which is a snapshot taken at the Yosemite National Park with the Yosemite Upper Fall in the background and a meadow with a lake in the foreground. The unperturbed lake surface provides a mirror-like reflection of the fall and the mountain range and is a perfect illustration of a very high DOI surface.

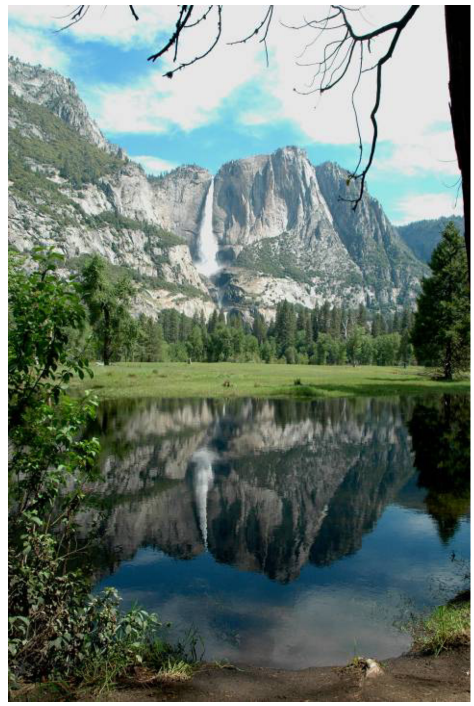

Figure 1. Photographic illustration of a high DOI (lake) surface.

In Fig. 2, we compare two images of a duck on a pond. In Fig. 2a, the duck is resting calmly and motionlessly on a very still pond. Note that there are hardly any ripples on the pond surface and the reflection of the duck is sharp and includes many details. On the other hand, in Fig. 2b, the duck is in motion and the pond surface now has an obvious "texture" (ripples) to it. Consequently, the reflection of the duck on the surface of the pond is blurry and has little or no details.

DOI of Inkjet Photo Papers

The illustrations above demonstrate the concept of DOI and its dependence on surface texture. A similar concept can be applied to inkjet photographic paper and surfaces, except that in this case, we are concerned about the DOI appearance of a printed substrate, generally under "normal" viewing conditions and distances. In Fig. 3, we show the reflection of a window blind with a potted plant on two inkjet photo paper samples (A & B). Both samples are printed in full black. It should be clear from these images that Sample A has high DOI since the reflection of the window blind and potted plant is clear & sharp, whereas Sample B has low DOI since the reflection is fuzzy and blurry.

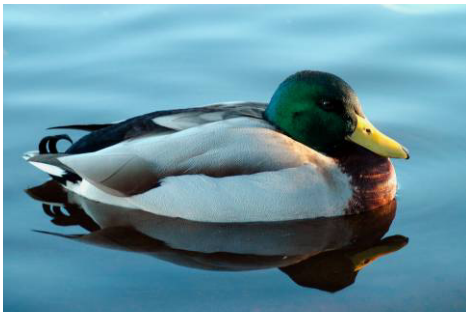

Figure 2a. Illustration of a high DOI (pond) surface with a clear & sharp reflection of the duck

Figure 2b. Illustration of a low DOI (pond) surface with a blurry reflection of the duck

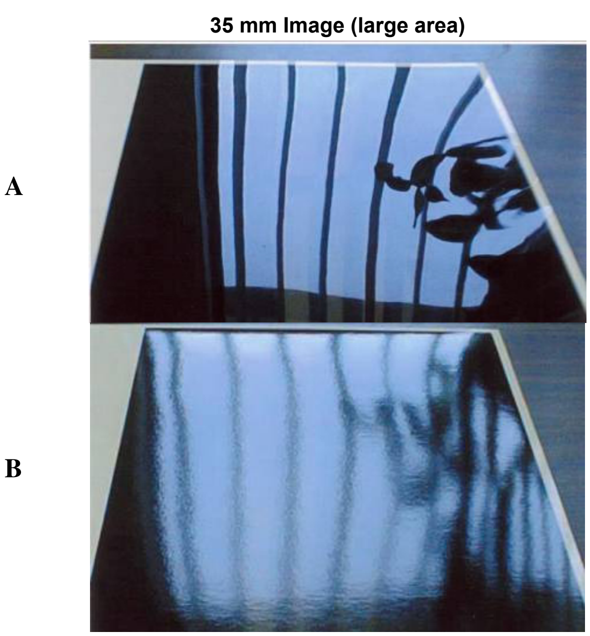

Figure 3. DOI on printed inkjet photo papers

Why do we care about the clarity of the reflection on the photo paper? The answer lies in the belief that the clarity of the reflection is a direct consequence of the texture of a surface, which apparently has strong influence on how we perceive the appearance of a surface, particularly that of a photograph. Based on this premise and the observation that DOI can be gauged by the quality (sharpness & contrast) of a reflected image (in particular, line edge and edge quality), we developed a new instrument for DOI measurement that can be applied to the evaluation of paper and other surfaces.

The principle and the design of the instrument were introduced recently.[1] An early version of the instrument has been applied in another study on inkjet media and the results were reported in NIP19.[2]

Measurement Principle & Implementation

The basic principle behind our DOI measurement technique involves projecting a sharp edge onto a surface, and capturing the reflected image using a solid state area or line sensor, e.g. CCD or CMOS. From the digitized image (Fig. 4a), a reflectance profile (or, the Edge Spread Function, ESF) is obtained (Fig. 4b) and analyzed to obtain a measure of the DOI of the sample-under-test. The main idea in this method is similar to the idea of obtaining the MTF (Modulation Transfer Function) of an imaging system from the ESF.

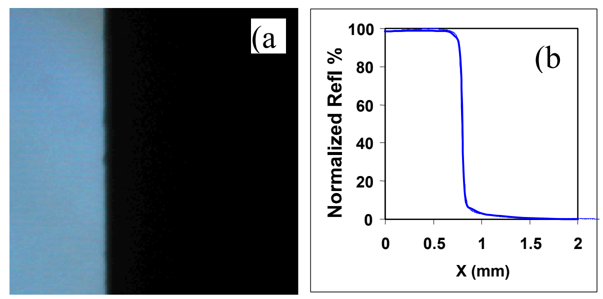

Figure 4. The reflected image of a sharp edge (a) and the corresponding edge spread function (b)

The method to obtain the DOI measures works as follows. From the ESF, we first obtain the Line Spread Function (LSF) by its derivative (Fig. 5a). Ideally, if the surface was perfectly smooth, the ESF would be a step function and the LSF would be a delta function with zero width. Also, the MTF is the LSF in the frequency domain. Surface quality information such as the DOI, image clarity, or sharpness can be obtained by characteristics in the LSF or the MTF. In the LSF the important features are peak height and halfwidth.

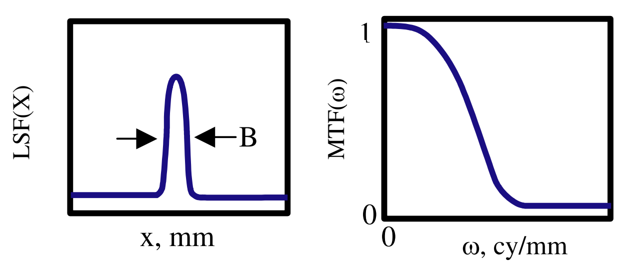

Figure 5. LSF obtained as the derivative of the ESF and MTF as the LSF in the frequency domain.

As shown below, we have found that the halfwidth of the LSF and the inverse of the halfwidth are very good (obviously not independent) measures of DOI. The halfwidth is reported as blurriness (B) in mm and the inverse of the halfwidth as sharpness (S) in mm^{-1}. The lower the blurriness or the higher the sharpness, the higher is the DOI (Distinctness of Image) of a surface.

The ESF contains more information than DOI alone, e.g., the magnitude of the leading edge reflectance which is related to specular gloss. We have demonstrated[1] that the leading edge reflectance, after calibration, is a good estimate of 60° gloss.

The above DOI measurement principle has been implemented in a new commercial, portable instrument called the DIAS (Distinctness of Image Analysis System) as shown in Fig. 6.[3]

Figure 6. DIAS – Distinctness of Image Analysis System

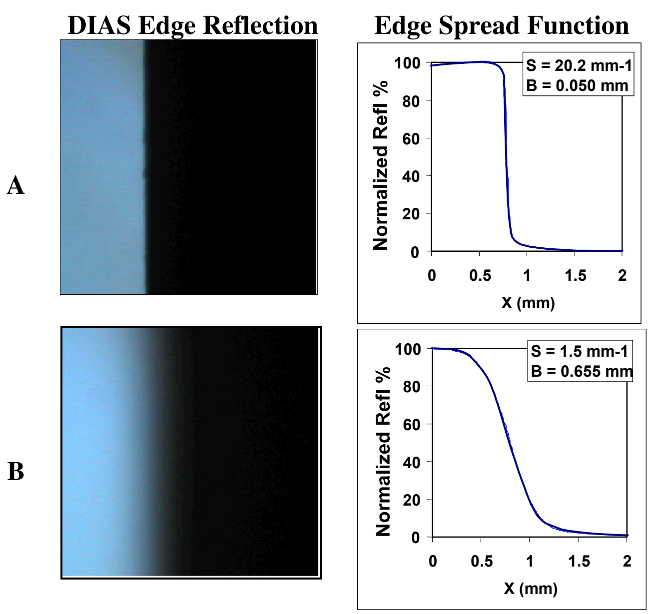

Figure 7. Typical DIAS results: edge reflection (a) and corresponding ESF and DOI sharpness & blurriness (b)

In the DIAS, a sharp edge is projected onto the sample-under-test and the reflection is captured using a digital CCD camera with microscopic optics (5 μm/pixel). The field of view is approx. 2.5 × 2.5mm. Typical results obtained from the DIAS are shown in Fig. 7. In this figure, the reflected images of the sharp edge on Samples A & B in Fig. 3 are shown in (a) and the corresponding ESF are in (b)

Correlation Between Visual Ranking and Objective Measurements

To establish the efficacy of the DIAS and our objective DOI measurement method, we designed a method to facilitate visual assessment of DOI in order to establish the correlation between visual ranking and objective measurements. In this method, a laptop computer is used in a room with no lights on and minimal ambient light. The assessor uses the sample as a reflector (resting on the laptop keyboard) to view the image on the laptop display. The images projected from the display are simple black/white line patterns with 50% duty cycle and various line spacing. Figure 8 shows simulated reflections from two samples with different DOI. The assessor uses the arrow keys on the laptop keyboard to cycle through the available line spacing (only one image with a single line spacing is projected at one time). The assessor is instructed to note the minimum line spacing for which the reflection contains resolvable lines. The final results are then scaled to a scale of 1 to 10, 1 for the lowest DOI and 10 for the highest. Clearly, the results are subject to differences in visual acuity of the assessors and their definition of "resolvable". Such subjectivity does introduce variability and in our experiment, we minimize such variability by getting the average of a reasonably large group of assessors.

The correlation between subjective DOI ranking and objective DIAS DOI measurements for 40 commercial, unprinted inkjet photo paper samples is shown in Fig. 9: DOI blurriness (mm) in (a) and DOI sharpness (mm-1) in (b). The papers are of the microporous, "instant-dry" type, with the 60° gloss in the range of 30-90.

A correlation between both DOI sharpness or DOI blurriness with visual ranking is clearly shown in Fig. 9. Interestingly, DOI blurriness (Fig. 9a) is linearly related to visual DOI ranking, whereas sharpness is related to visual ranking in a power law relationship (which is not surprising since sharpness is simply the inverse of blurriness and blurriness is linearly related to visual ranking). In this paper, we will use primarily sharpness as the measure of DOI.

As pointed out earlier, while visual ranking is essential to establish the relationship between perceptual and objective measurements, one must recognize its limitation also, i.e., it is subject to variability in the assessor's visual acuity and subjectivity in defining resolvability. Here lies the most important advantages of the objective measurement method over the visual ranking method – objectivity and reproducibility. The standard error (i.e. stdev/mean) is as high as 40% at low DOI and around 18% at higher DOI for the visual method. As for the instrumental (DIAS) method, the standard error is about 9% when measurements are made randomly across the sample and less than 1.5% when measurements are made with the instrument stationary.

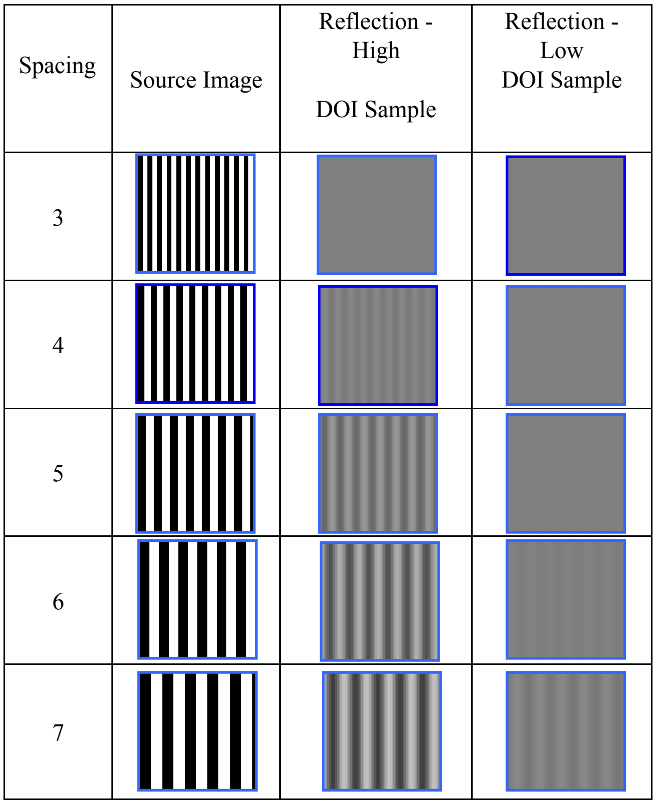

Figure 8. Source target & simulated reflections in subjective ranking experiment

Correlation Between DOI and Specular Gloss

DOI, being defined as the sharpness or clarity of a reflected image on a surface, can also be viewed as a measure of the deviation or dispersion from specular reflection (gloss). Hence, in principle, there is no logical reason to believe that DOI should be related to the magnitude of specular gloss in any predictable fashion. Indeed, one can have a high gloss surface with a low DOI and vice versa. Such an argument is substantiated by the data shown in Fig. 10. The specular gloss was measured by means of a BYK Gardner Micro-TriGloss glossmeter.

It has been suggested by some that 20° gloss can be used to estimate DOI. Based on the results in Fig. 10, it is clear that such is not the case since the 20° gloss results are quite independent of DOI sharpness for this group of inkjet samples.

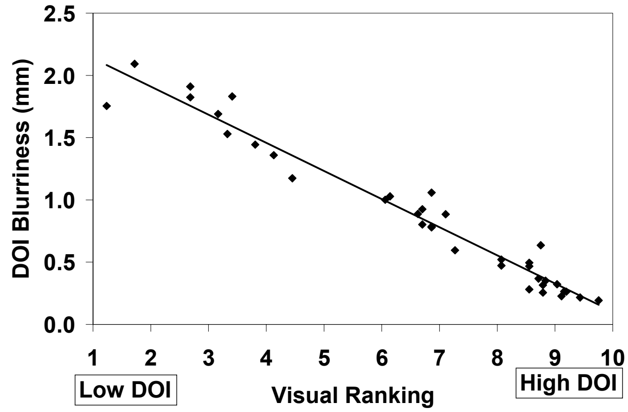

Figure 9a. DOI Blurriness obtained from DIAS vs. visual ranking for 40 unprinted inkjet photo papers

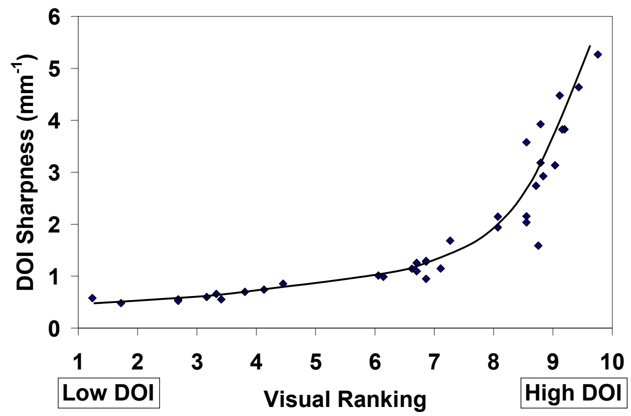

Figure 9b. DOI Sharpness obtained from DIAS vs. visual ranking for 40 unprinted inkjet photo papers

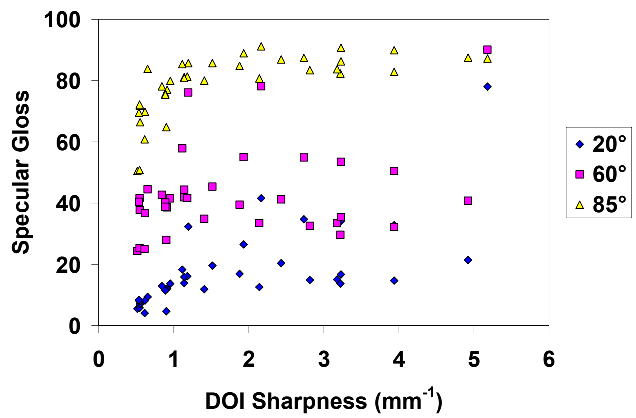

Figure 10. Correlation (or the lack of) between specular gloss and DOI sharpness.

Correlation Between DOI and Surface Roughness

Since it is believed that DOI is primarily controlled by the surface texture, it is logical to speculate that there must be some observable correlation between DOI and surface roughness. In this experiment, surface roughness of the inkjet photo paper samples were measured using a Mitutoyo SJ-201P surface profilometer with a 10 •m tip and a 2.5 mm scan length. The results are shown in Fig. 11. From this figure, while there appears to be some correlation between the surface roughness measured in terms of Ra (arithmetic average in the z-direction), it is nonetheless a rather weak and "noisy" one, suggesting that either Ra is not the best characterization of surface texture for DOI prediction, or that there may be other physical characteristics that come into play also.

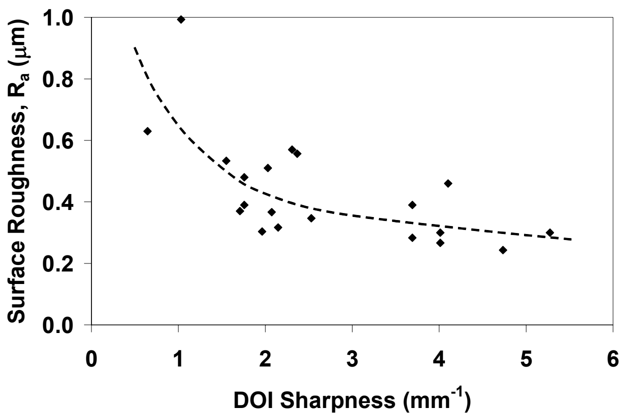

Figure 11. Correlation Between Surface Roughness & DOI Sharpness

Effect of Printing on DOI – 100% Ink Coverage

An important piece of information in the design of inkjet photo paper (or ink) is the compatibility between the ink and the paper. To investigate the impact of printing on DOI, a test target[4] containing multiple color patches of CMYKRGB at different tint levels was used and the results analyzed to discover the difference (if any) between printer manufacturers (hence print engine design, ink set or both) and the effect of tint level.

In this study, two printers were used: HP5500 and Epson R800, both with pigmented ink sets. The same set of 40 inkjet photo paper samples, used in the previous testing, was used in this testing. Most of this set of papers are of the micro-porous, "instant dry" type.

We found that printing in general diminishes the DOI, except for the very low DOI papers as can be seen from Figs. 12 and 13. This data is based on the entire set of inkjet photo papers and 100% ink coverage. However, the extent of the decrease is very much dependent on the printer (i.e., details on the head design, ink volume, ink type and the writing strategy) and the paper type (e.g., coating materials and microstructures). Generally, the DOI sharpness of print vs paper correlation has a positive slope for the colors studied (CMYK), hence, it appears that the higher the DOI of a substrate, the higher the print DOI.

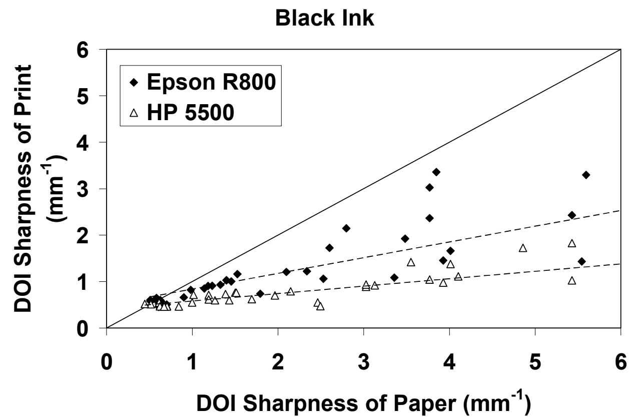

Figure 12. Effect of printing on DOI. Data shown for 100% black ink and two printers for entire set of papers studied.

In Fig. 12, we also compare the DOI sharpness of the 100% black printed samples vs. the unprinted substrate for two printers, an Epson R800 and an HP 5500. In both cases, the OEM ink set was used and in the case of Epson printer, the clear "gloss optimizer" was disabled. As shown in this figure, for the same substrate, the Epson prints typically have higher DOI values than the corresponding HP prints. The difference in DOI between the two printers, however, can vary quite substantially from paper to paper.

From the results in Fig. 13, a similar conclusion regarding the effect of printing on DOI can be drawn for CMY inks to those for the black inks. First, printing diminishes DOI in general, but the extent of the decrease is lower for the CMY inks than the black ink. Second, the Epson R800 produces higher DOI prints than the HP 5500. Since we do not know the design details of either printer and its corresponding ink set, we cannot really provide any explanations for observed differences. Discovering the mechanistic reasons for the difference would certainly provide further insight into the optimization of a very important parameter in photo inkjet paper design.

Effect of Printing on DOI at Different Tint Levels

The effect of printing on DOI at different tint levels for the set of inkjet photo papers studied seems to range widely from paper to paper and from printer to printer. Some general observations can still be made, however.

In Fig. 14, the DOI sharpness for two paper types (#1 and #36) at 4 tint levels was compared. The printer is the same (HP 5500) for the results in Fig. 14a and 14b.

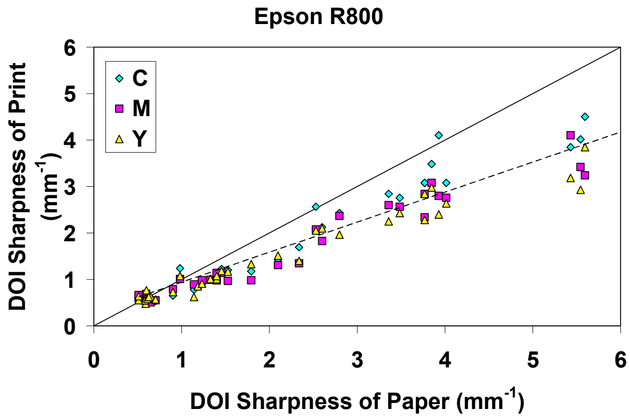

Figure 13a. Effect of printing on DOI. Data shown for Epson R800, 100% CMY inks, and the entire set of papers studied.

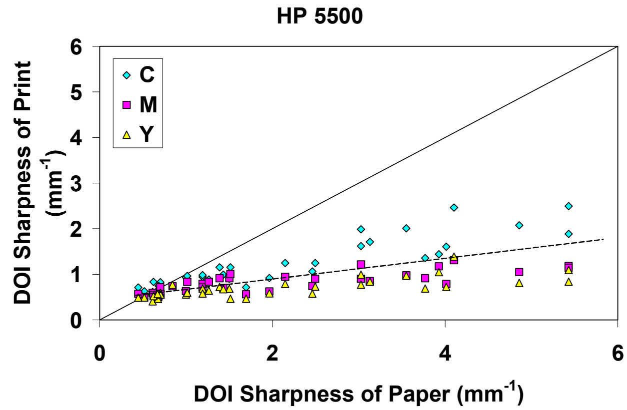

Figure 13b. Effect of printing on DOI. Data shown for HP 5500, 100% CMY inks, and the entire set of papers studied.

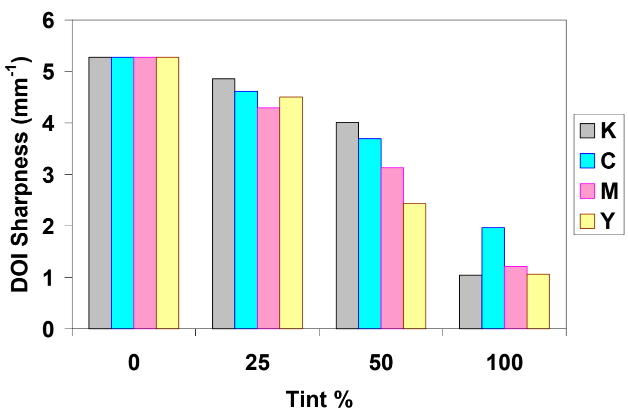

Figure 14a. Effect of Tint % on DOI, HP5500 on Paper 1.

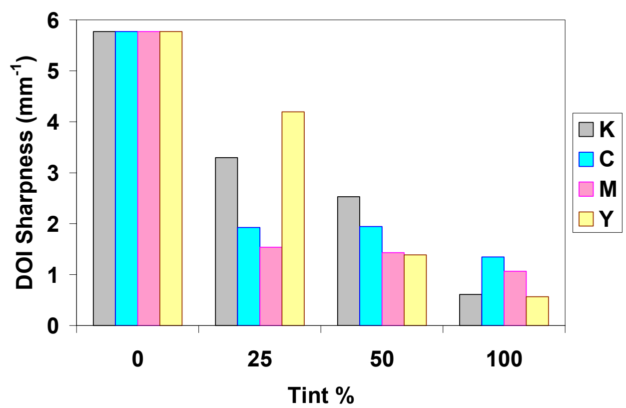

Figure 14b. Effect of Tint % on DOI, HP5500 on Paper 36

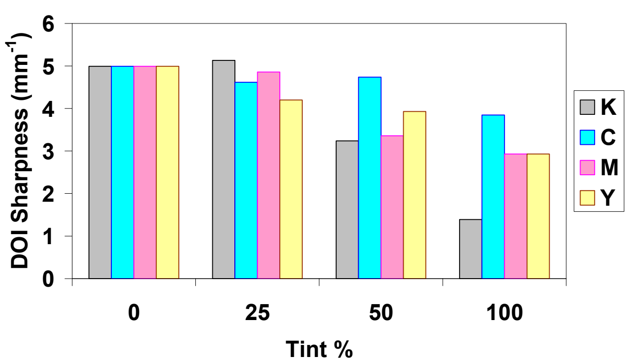

Figure 15a. Effect of Tint% on DOI, Epson R800 on Paper 1.

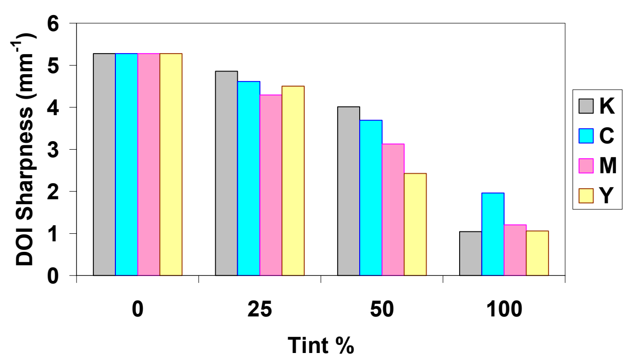

Figure 15b. Effect of Tint% on DOI, HP5500 on Paper 1.

It can be seen in Fig. 14 that printing on these two papers decreases the DOI, but the rate of decrease as a function of tint level differs quite substantially between the two paper types and among different colors. Again, understanding the mechanistic reasons behind such observations would be beneficial for making improvements in photo inkjet papers.

Figure 15 provides further insight into the difference between the two printers used in this study. The drop in DOI is quite different for the two printers and the dependence on ink color and tint level is quite different also.

As pointed out earlier, the dependence of DOI on printer, ink and paper ranges quite a bit for the combinations reported in this study. Hence, the importance of a reliable method and instrument for making DOI measurements would appear to be crucial for making advancements in the technology of photo inkjet paper.

Summary

1. Distinctness of Image (DOI) is receiving increasing attention as an important appearance attribute that correlates with the customer's perception of "photo-like" quality in digital photography.
2. A new technique for DOI measurement was introduced recently and is applied to the evaluation of inkjet photo papers in this study.
3. DOI is the sharpness and clarity of a reflected image from a surface. In our technique and commercial instrument, a sharp edge is projected onto a sample and the reflection is captured and analyzed digitally. Specifically, a blurriness parameter and its inverse, sharpness, are obtained from the edge spread function (ESF) and its derivative the line spread function (LSF).
4. The technique and the instrument are applied to evaluate 40 inkjet papers. The papers are mostly of the microporous, "instant-dry" type, with 60° gloss in the range of 30-90. The printers used are an Epson R800 and an HP 5500, both with pigmented inks.
5. The DOI results (blurriness and sharpness) correlate well with subjective (visual) ranking of the set of papers. Since blurriness and sharpness are not independent attributes, DOI sharpness is used in this report since it increases with DOI.
6. DOI sharpness does not correlate with conventional specular gloss measurements.
7. DOI sharpness is marginally correlated with the traditional surface roughness parameter Ra, suggesting that other physical measures of surface texture may be needed to better correlate with visual ranking and objective DOI.
8. Printing diminishes the DOI for most of the paper samples for the two printers studied. The decrease is typically smaller for the Epson R800 than the HP 5500.
9. The effect of tint level on DOI in general is quite complicated. However, DOI typically decreases with increasing tint% but the rate of decrease varies substantially from paper to paper.
10. The results in this paper demonstrate that the methodology and the instrument described in this paper provide a new tool for the study of a very important appearance attribute for digital photographic printing.

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