Color Tolerance Prediction for Recycled Paper Based on Consumers’ Awareness

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Abstract: Consumers’ tolerance of the color of recycled paper was evaluated by the visual assessment of such paper by 30 Japanese university students. The assessment was performed to measure color tolerance using 266 color samples in eight conditions specifying the situation of paper as (1) “either paper is recycled or not recycled,” (2) “whether you will buy/use,” and (3) “use for office paper or for workbook paper.” The responses of the subjects were sorted out quantitatively in terms of the colorimetric values of color samples and then correlated with International Organization for Standardization (ISO) brightness and CIE whiteness. Both the ISO brightness and CIE whiteness were found to be dependent on hue factors and also to be restricted for use in direct representation of the consumers’ responses to paper quality. Since the consumers’ evaluation of paper quality is due to visual whiteness, we propose a new equation to predict the consumers’ tolerance of paper color, in which the equation contains two factors concerning the color distance from the white point and the hue impact. The new tolerance equation was confirmed to predict the consumers’ tolerance successfully, particularly when the consumers are aware that the paper is recycled.

Key words: color tolerance; visual assessment; ecological paper color; equation of tolerance

INTRODUCTION

Recently, forest/water pollution from the manufacturing process and waste have become serious environmental issues for the paper manufacturing industry.1 Accordingly, it has become more common to find recycled paper products in the market in recent days, as recycled paper has an advantage over virgin paper from an environmental viewpoint, i.e., reducing the demand on forests, reducing greenhouse gas emissions, recovery of solid-waste, etc.1–3 However, there are two major drawbacks for recycled paper: one is the high cost of manufacturing recycled paper and the other is the bleaching process.4 Those two drawbacks are caused by the recycling process used to produce recycled paper with the same specifications as virgin paper. Fluorescent whitening agent (FWA) is conventionally used in the bleaching process5 to make recycled paper as white as virgin paper.6 As FWA is costly and not environmentally friendly, the resulting recycled paper will become less and less favorable with the use of FWA in terms of cost and environment. Considering the social requirements for recycled paper, we should reduce the environmental impact by reducing the amount of FWA, but recycled paper with less FWA treatment would not be accepted by consumers because of its poor appearance. Here we should consider various factors to optimize the processing of recycled paper, including production cost, consumers’ acceptance, and life cycle assessment.7 At present, it seems there is no criterion available for optimizing the recycling process and thus recycled paper with the same quality of appearance costs more than the virgin paper. Consumers might be tolerant with recycled paper of lower quality because of their environmental consciousness, and so it might be useful from a practical viewpoint to set a standard of visual whiteness for recycled paper in terms of the consumers’ tolerance.
In this article, the consumers’ tolerance for visual whiteness (“whiteness” in general) was evaluated from the questionnaires concerning the acceptance of colored paper for office use in the first step. This evaluation is intended to determine an adequate criterion for paper quality through consumers’ tolerance of the visual whiteness of recycled paper. In the second step, the tolerance of paper quality was correlated with the chromatic value, the International Organization for Standardization (ISO) brightness and Commission Internationale de l’Eclairage (CIE) whiteness, since ISO brightness and CIE whiteness are commonly used to evaluate visual whiteness in the paper industry. The proposed equation is expected to serve as a criterion for consumers’ tolerance of paper quality.

WHITENESS OF PAPER

Most studies on the quantitative evaluation of whiteness have been based on a visual assessment of surface visual whiteness. A chemical bleaching process was introduced in the 18th century, and FWAs were invented in the 20th century to produce whiter products in the fabric and paper industry. In the paper industry, whiteness is a criterion of paper quality, and whiter paper is regarded to be of better quality. In this context, the accurate measurement of whiteness is indispensable to the control of paper quality. Since Judd and Nickerson proposed the idea of whiteness assessment in 1935, extensive studies have been performed to improve the assessment of whiteness. CIE whiteness is commonly used for the optical assessment of paper appearance in the paper industry. Alternatively, ISO brightness (ISO 2470), which is a measurement of diffuse blue reflectance factor at an effective wavelength of 457 nm, is also used as a measurement of the whiteness of paper, board, and pulps. Japanese industrial standards (JIS) specify a CIE whiteness formula (JIS Z 8715) and ISO brightness (JIS P 8148) as standard methods for measurement of whiteness.

A VISUAL ASSESSMENT

A visual assessment relies on the paper color choice of subjects when they are notified of the recycled fiber content. To ensure statistical accuracy, the assessment in this study was carried out with 30 Japanese university students. The subjects were asked to select acceptable colors corresponding to the eight different conditions shown in Fig. 1. The conditions were premised on two types of paper: office paper for printing with a printer and workbook paper for writing by hand; two intention types: use and purchase; and awareness of recycled status, in terms of no mention and mention of recycled status. The subjects were asked to indicate the border color between acceptable and unacceptable colors in each hue column on the color palette (Fig. 2).

The surveys were carried out in two sets. The first set conducted without mention of recycled paper status.
FIG. 4. Color distribution of the 266 color samples on (a) a $C^* - L^*$ diagram and (b) a $a^* - b^*$ diagram.

FIG. 5. The ISO brightness of the 266 color samples. Here N denotes Neutral, R denotes Red, O denotes Orange, Y denotes Yellow, G denotes Green, B denotes Blue, and P denotes Purple.

FIG. 6. The CIE whiteness of the 90 color samples out of the 266 color samples, which satisfy the condition of the CIE whiteness.

FIG. 7. The limited range of the CIE whiteness is indicated by the dashed line. Colors above the dashed line fit in the CIE whiteness criterion.

FIG. 8. The observed tolerance $T_{ob}$ for N, R1, R2, and R3 of Re-O-Use plotted against the lightness level.
second set was conducted with mention of recycled status, with the same subjects who responded the first set. The survey was carried out under D65 illuminant condition with a viewing cabinet.

As shown in Fig. 2, the color palette is made of one neutral or achromatic category and six hue categories including Neutral (N), Red (R), Orange (O), Yellow (Y), Green (G), Blue (B), and Purple (P). As very vivid colors cannot be acceptable as paper colors because of poor legibility, the starting RGB values were fixed as follows: N (75/75/75), R (150/0/0), O (150/75/0), Y (150/122/0), G (0/150/0), B (0/75/150), and P (150/0/150). Each hue category was then extended to three levels by de-saturating the colors. For example, grayish red (150/75/75) and more grayish red (150/112/112) were added to the hue category R. A total of twelve intermediate colors between the selected colors and white were created. As an example, illustrated in Fig. 3, 42 reddish colors were generated in a $3^3$ array starting with red (150/0/0). Subsequently, a color palette that consisted of 266 previously selected color samples was composed. The created 266 color samples were printed by Laser beam printer 5610 (Canon, Inc.) on DIN A2 size paper. A piece of normal white copier paper (not recycled paper) was used for preparing the color palette.

### TABLE I. Correlation coefficients ($r$) between color tolerance of eight conditions and color co-ordinate values.

<table>
<thead>
<tr>
<th>Eight conditions</th>
<th>Brightness (ISO), $n = 266$</th>
<th>$L^*$, $n = 266$</th>
<th>$C^*$, $n = 266$</th>
<th>$a^*$, $n = 266$</th>
<th>$b^*$, $n = 266$</th>
<th>$h$, $n = 266$</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-Use</td>
<td>0.82</td>
<td>0.61</td>
<td>-0.63</td>
<td>-0.17</td>
<td>-0.20</td>
<td>0.16</td>
</tr>
<tr>
<td>O-Buy</td>
<td>0.74</td>
<td>0.68</td>
<td>-0.55</td>
<td>-0.14</td>
<td>-0.19</td>
<td>0.25</td>
</tr>
<tr>
<td>W-Use</td>
<td>0.86</td>
<td>0.50</td>
<td>-0.68</td>
<td>-0.20</td>
<td>-0.21</td>
<td>0.17</td>
</tr>
<tr>
<td>W-Buy</td>
<td>0.83</td>
<td>0.65</td>
<td>-0.64</td>
<td>-0.17</td>
<td>-0.21</td>
<td>0.17</td>
</tr>
<tr>
<td>Re-O-Use</td>
<td>0.90</td>
<td>0.46</td>
<td>-0.75</td>
<td>-0.21</td>
<td>-0.23</td>
<td>0.13</td>
</tr>
<tr>
<td>Re-O-Buy</td>
<td>0.82</td>
<td>0.52</td>
<td>-0.66</td>
<td>-0.17</td>
<td>-0.20</td>
<td>0.13</td>
</tr>
<tr>
<td>Re-W-Use</td>
<td>0.89</td>
<td>0.51</td>
<td>-0.74</td>
<td>-0.20</td>
<td>-0.22</td>
<td>0.11</td>
</tr>
<tr>
<td>Re-W-Buy</td>
<td>0.85</td>
<td>0.54</td>
<td>-0.69</td>
<td>-0.18</td>
<td>-0.20</td>
<td>0.13</td>
</tr>
</tbody>
</table>

FIG. 9. The observed color tolerance $T_{ob}$ of Re-O-Use plotted against the ISO brightness, where the correlation coefficient $r = 0.90$. See Table I for details.

FIG. 10. The observed color tolerance $T_{ob}$ of Re-O-Use plotted against the CIE whiteness, where the correlation coefficient $r = 0.46$. See Table I for details.

FIG. 11. The gray lines denote the mean values of the lightness level across the 19 hue categories for each instruction. The red line indicates the mean value for the lightness level across the 19 hue categories with the eight instructions.

COLOR research and application
MEASURING THE COLOR SAMPLES

The 266 color samples on the printed paper were measured in terms of \( L^* \), \( a^* \), and \( b^* \) values of the CIELAB color scale by a CM-3600d spectrophotometer (Konica Minolta) under D65 illuminant conditions with a 10-degree field of vision.

The near-white colors, which have high \( L^* \) value, and low \( C^* \), \( a^* \), and \( b^* \) value, were selected as shown in Fig. 4 for the assessment. Those near-white colors were expected to reveal the threshold of the tolerance for paper color in each individual judgment.

Whiteness/brightness is a critical component for the consumers’ decision to use or purchase paper products. If the paper whiteness is at the level of general paper, almost all consumers will accept the product. In this context, we evaluated the whiteness/brightness of the colored paper samples in terms of the ISO brightness and the CIE whiteness, and examined how visual perception is related with optical properties.

The ISO brightness is specified by the reflectance of the prescribed single wavelength (457 nm) in the blue region of the spectrum. The colored paper samples were subjected to ISO brightness measurements as shown in Fig. 5, in which the ISO brightness is characteristically higher for bluish color samples.

The CIE whiteness \(^{12,16} \) of the colored paper samples was calculated according to the definition of the CIE whiteness. The CIE whiteness (D65/10°) value \( W \) is defined as:

FIG. 12. The \( \Delta E \) dependence of the observed color tolerance \( T_{ob} \) when the observed color tolerance is over 30%. 

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\[ W = Y_{10} + 800(x_{10} - x_{10}) + 1700(y_{10} - y_{10}) \]  \hspace{1cm} (1)

where \( Y_{10} \) is the \( Y \)-value, \( x_{10}, y_{10} \) are the chromaticity coordinates of the sample and \( x_{w,10}, y_{w,10} \) are the coordinates of the reference white. (For D65/10' \( x_{w,10} = 0.3138, y_{w,10} = 0.3310 \)) The material is regarded as white on the condition that \( W \) lies within the limits given by \( 40 < W < (5Y_{10} - 280), \) \(-4 < T_{w,10} < 2 \). The range of white color is too narrow according to the definition of CIE whiteness.11 Figure 6 shows the range of the CIE whiteness. Here 90 color samples satisfy the condition among the original 266 color palette.

Figure 7 shows the range of the CIE whiteness with the dashed line, where the CIE whiteness for 90 colors above the dashed line satisfies the condition specified by the CIE whiteness, Eq. (1), among 266 colors in the original color palette.

**RESULTS**

Based on the frequency of choices the subjects made, a percentage was calculated for each color sample for each of eight conditions (see Fig. 1). Therefore, there are eight percentage values for each color sample. In this study, the percentage value is labeled \( T_{ob} \), and called “the observed tolerance.” In addition, the eight evaluation items are abbreviated...
ated as follows: Using as office paper (O-Use), Buying as office paper (O-Buy), Using as workbook paper (W-Use), Buying as workbook paper (W-Buy), Using as recycled office paper (Re-O-Use), Buying as recycled office paper (Re-O-Buy), Using as recycled workbook paper (Re-W-Use), and Buying as recycled workbook paper (Re-W-Buy). For example, the observed tolerance $T_{ob}$ values for hue values N, R1, R2, and R3 are depicted under condition of Re-O-Use as a function of lightness level as shown in Fig. 8.

**FIG. 14.** The observed tolerance $T_{ob}$ compared with the predicted tolerance $T_{pr}$ by Eq. (5) when the observed color tolerance is over 30%.

Does the ISO Brightness or the CIE Whiteness Represent the Observed Color Tolerance?

If the consumers’ color selection depends on the visual whiteness of the paper, the correlation coefficient should be high between brightness/whiteness and the color tolerance. Table I summarizes the correlation coefficients ($r$) where the ISO brightness and the CIE whiteness are confirmed to have a high correlation with the color tolerance of the eight conditions.

These correlation results suggest the possibility that either the ISO brightness or CIE whiteness may represent color tolerance. Now we look at more quantitative details of the correlation between the ISO brightness/CIE whiteness and the color tolerance.

As shown in Figs. 9 and 10, the relation between the ISO brightness/CIE whiteness and the observed color tolerance $T_{ob}$ is influenced by hue. In other words, the subjects respond with different tolerance to the same condition according to hue. For example, the bluish samples are marked with a lower
tolerance despite their having a higher ISO brightness/CIE whiteness than that of the other hues (Figs. 5 and 6).

The CIE whiteness value cannot be applied directly to evaluate the consumers’ tolerance because it is defined only in the range of 40 < W < (5Y_10W-280) and −4 < T_w,0 < 2, so that its application is restricted within this range. To see the details of the observers’ choices, the mean values of lightness were evaluated for each hue. Here each subject was asked to choose the border color on each hue column in the color palette (see Fig. 2). Then the subject was asked to indicate a lightness level between 1 and 14, below which the paper color is not acceptable. The lightness levels of the chosen samples by the 30 subjects were averaged to yield the “mean value of lightness level” for the corresponding hue.

However, the mean values of lightness level of consumers’ responses to the conditions were in some cases below the lower limit of the CIE whiteness indicated by the dashed lines in Fig. 11.

In conclusion, the consumers could accept a paper that is not extremely white, and use/buy a slightly colored paper. We examine the quantitative evaluation for the consumers’ color tolerance of paper in the next section.

### The Color Difference (ΔE) and Color Tolerance

In the preceding section, we found that the color tolerance depends on the degree of visual whiteness (regardless of the definition of whiteness) and that the consumers could be more tolerant of yellowish colors than bluish colors. We may assume that the color tolerance decreases with the distance from the white point of L*, a*, b* values at 100, 0, 0. We calculated the color difference ΔE\(_{ab}\)^* of each color on the color palette from the white point.

\[
\Delta E_{ab}^* = \sqrt{(100-L^*)^2 + (a^*)^2 + (b^*)^2}
\]  
(2)

The calculated ΔE_{ab}^* values for each color sample are not equally spaced, particularly for the colors that have higher intensity levels (Table II). For example, the first or second level of whiteness exhibits an enhanced spacing in the hue1 group. Red and purple samples have higher ΔE values than other colors. This fact confirms the dull reaction to the red and purple samples, where the mean value of the lightness level of the red and purple row are higher than that of other hues, as shown by the gray lines in Fig. 11. In the next step, we correlate the color difference to the results of the color tolerance test, in which the values lower than 30% tolerance are discarded as disapproved tolerances.

The tolerance was indeed highly correlated with the color difference, as we assumed a priori. Although the tolerance data scatter considerably because of their statistical nature, the consumers’ color tolerance for paper could be expressed by the following linear Eq. (3):

\[
T_{pr} = - K_{AE} \Delta E_{ab}^* + \text{Const.}
\]  
(3)

where \(T_{pr}\) denotes the predicted color tolerance, \(K_{AE}\) the coefficient of \(\Delta E_{ab}^*\), and \(\text{Const.}\) a constant. A distinctive trend was observed with hue factor scattering in Fig. 12, where the observed tolerances systematically deviate from the predicted tolerances, depending on hue groups from above to below the predicted line represented by Eq. (3), in the order of (purple, blue), green, red, orange, and yellow, as can be seen in Fig. 13. Accordingly, the correction should be made in Eq. (3) with respect to each hue to make a universal tolerance equation.

The tolerance Eq. (3) now includes the term depending on the hue value and the hue difference with respect to the yellowish hue, where the tolerance at the same color difference \(\Delta E\) will be higher for the yellowish hue than for the bluish or purplish hue. The present results indicate that Eq. (3) could be corrected by the hue term: \(h_{ab} = \arctan(b^*/a^*)\).

The \(h_{ab}\) average values and standard deviations of each hue group samples are \(\overline{h}_B = 33(\sigma = 9.94), \overline{h}_G = 67(\sigma = 6.30), \overline{h}_Y = 81(\sigma = 6.49), \overline{h}_C = 117(\sigma = 14.87), \overline{h}_B = 255(\sigma = 21.51),\) and \(\overline{h}_P = 340(\sigma = 6.36).\)

Here we define the hue difference \(\Delta h_{80}\) as the distance to a particular hue from the yellowish hue specified by \(h_{80} = 0.\)

\[
\Delta h_{80} = \min(|h_{ab} - 80|, |440 - h_{80}|) \quad (0 \leq \Delta h_{80} \leq 180)
\]  
(4)

The slope \(K_{AE}\) and the intercept \(\text{Const.}\) in Eq. (3) are not universal, but vary with the hue groups. To make a universal tolerance equation, we modify Eq. (3) by taking into account the hue difference \(\Delta h_{80}\) as follows:

\[
T_{pr} = - K_{AE}^* \Delta E_{ab}^* + \text{Const.}^* (\Delta h_{80})
\]  
(5)

\[
K_{AE}^* (\Delta h_{80}) = K_{AE} \times \{(x_y - x_B) \Delta h_{80}/180\} + x_Y
\]  
(6)

\[
\text{Const.}^* (\Delta h_{80}) = \text{Const.} + \beta_B + (\beta_B - \beta_Y) \Delta h_{80}/180
\]  
(7)

In Eqs. (6) and (7), \(x\) and \(\beta\) denote the slope and the intercept of a hue group, respectively. \(K_{AE}^*\) and \(\text{Const.}^*\) are not constant, but linear functions of \(\Delta h_{80}\). Table III summarizes the \(\Delta h_{80}\) dependence of \(K_{AE}^*\) and \(\text{Const.}^*\), in which the coefficients of \(\Delta h_{80}\) are given for each condition. When the value of Eq. (5) exceeds 100, we assume that the tolerance is 100.
Equation (5) is optimized to fit the tolerance data, and a universal equation is now proposed for the tolerance threshold of the “recycled office paper for use” as:

\[
T = -(0.008\Delta h_{80} + 4)\Delta E + 0.01\Delta h_{80} + 125 \tag{8}
\]

Similarly, the color tolerance could be predicted for other conditions readjusting the coefficients of Eq. (5). Table IV and Fig. 14 show the correlations between the observed tolerance \(T_{ob}\) and the predicted tolerance \(T_{pr}\) by Eq. (5).

**CONCLUSION**

1. The consumers will accept office paper with a much wider range of colors when they are aware that the paper is being recycled. For example, the tolerance level increases to 80% for paper of the color (Y1, 11) when the consumers know that the paper is recycled, whereas the tolerance level drops to 46.7% without the knowledge of recycled status. That is, the consumers are conscious of environmental issues and are tolerant of the lower quality of recycled papers.

2. The conventional ISO brightness and CIE whiteness are not suitable to represent consumers’ tolerance of paper. The CIE whiteness is based on psychometric studies of visual whiteness, so that a bluish color is much whiter than a yellowish color. However, the present visual assessment confirms that consumers exhibit a higher color tolerance for using/buying the yellowish paper than they do for the bluish near-white color. The recycled paper is more tolerated with regard to whiteness than the virgin paper, so that the recycled paper is not required to be bleached to a “visual whiteness” so much as the virgin paper.

3. The tolerance equation Eq. (5) was proposed to predict consumers’ tolerance of office paper/workbook paper by taking into account the inverse correlation of the tolerance of the color difference from the white point of \(L^*, a^*, b^*\) values at 100, 0, 0. The equation includes the impact of hue in terms of hue angle value.

Tolerances predicted with this equation have a high correlation with observed tolerances, particularly when the consumers are aware that the paper is being recycled. The correlation is lower when the consumers are not notified of the recycled status.