Improving the Perceptual Uniformity of a Gloss Space

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Abstract

The perceptual gloss space defined in Pellacini et al. [9] could be used for quality control applications to bring similar benefits as seen in color with the use of CIELAB. However, a distance metric to relate all the dimensions in the space does not exist, and the space was only validated with the materials used to define the space.

The current space's distance metric does not allow relating differences in lightness to the other dimensions: contrast gloss and distinctness of image gloss. The lightness perception uniformity of the space was first evaluated in a psychophysical study, where the observers' lightness discrimination was found to decrease as lightness increased. A function was derived to model the lightness perception observed and it was included into the distance metric of the space.

The space uniformity around sixteen positions in the gloss space was evaluated in a second psychophysical study to assess the overall space uniformity. The space was found to be perceptually non-uniform outside the samples used when the space was created. Also, an improved gloss difference equation that takes into account the non-uniformity of the space is presented, showing a statistical significant improvement over the current gloss difference equation of the space and reducing the STRESS value from 39.76 to 22.96.

Introduction

The CIELAB color space and the color difference equations defined in it have been widely used for quality control applications and to characterize input and output devices taking into account human color perception. When considering gloss perception, perceptual attributes defined as ASTM features (distictness-of-image gloss, haze, bloom, etc.) are used for quality control applications, and perceptual gloss spaces are discussed in the computer graphics literature.

The perceptual gloss space defined in Pellacini et al. [9] could be used for quality control applications to bring similar benefits as seen in color with the use of CIELAB. For example, the ability to set tolerances across multiple dimensions and the opportunity to have a single value to describe the perceptual distance between two materials.

However, some limitations still restrict the use of this perceptual gloss space in that regard. The first limitation is the need to locate the position in the space for a given real material, which could be accomplished by approximating material measurements with the underlying analytical model that defines the perceptual gloss space. The second limitation is the need to further characterize the relation between different dimensions in the space and to validate the space's perceptual uniformity.

This paper is going to focus on the uniform gloss space defined in Pellacini et al. [9], by first adding lightness to the gloss difference equation of the space, then the space uniformity will be evaluated, and finally an improved gloss distance measure will be presented.

The current space's distance metric does not allow relating differences in lightness to the other dimensions: contrast gloss and distinctness of image gloss. The lightness perception uniformity of the space was first evaluated in a psychophysical study, where the observers' lightness discrimination was found to decrease as lightness increased. Then, a function was derived to model the lightness perception observed and it was included in the distance metric of the space defined in Pellacini et al. [9]. It's important to note that the gloss perception using a common LDR display is studied in this work, and similar experiments would need to be performed to study the gloss perception of physical objects or when using HDR displays.

The perceptual uniformity around sixteen positions in the gloss space was evaluated in a psychophysical study. The results of our study show that the space is not perceptually uniform and improvements on the distance metric are needed to improve its uniformity outside the samples used to create the space. Finally, the results of the second experiment are used to derive an improved gloss distance measure of the space.

To summarize, the main contributions of this paper are:

- The inclusion of lightness to the gloss difference equation of the gloss space defined in Pellacini et al. [9].
- The validation of the gloss space uniformity, finding that the space is non-uniform outside the samples used to create the space in Pellacini et al [9].
- The creation of an improved gloss difference equation that takes into account the space non-uniformity.

Background

In Pellacini et al. [9], a perceptual space of glossy materials represented by the Ward BRDF model [15] was presented. Two different experiments were performed to find the dimensionality of the gloss space for a set of samples, and then to perceptually scale the axes to obtain a uniform space. Two dimensions were found to be enough to describe the gloss perception: contrast gloss (c), which describes the relation between the diffuse component and the specular peak, and distinctness of image gloss (d), which defines the sharpness of the reflections. Lightness (L^*) was added to define the diffuse component, and the mapping from the Ward BRDF model parameters to the perceptual parameters was defined as:

$$c = \sqrt[3]{\rho_s + \rho_d/2} - \sqrt[3]{\rho_d/2} \tag{1}$$

$$d = 1 - \alpha \tag{2}$$

$$L^* = f(\rho_d) \quad (3)$$

where ρ_d and ρ_s are the diffuse and specular reflectance, respectively, α is the Ward BRDF model parameter, and f corresponds to the CIELAB lightness function. The results of the experiment were also used to define a perceptual distance metric in the space:

$$D_{i,j} = \sqrt{[c_i - c_j]^2 + [1.78(d_i - d_j)]^2} \quad (4)$$

where $D_{i,j}$ is the perceptual distance between the samples i and j represented with the c and d space coordinates.

This space has successfully been used to evaluate the material discrimination dependence on the objects' shape and for different materials [14]. In Vangrop and Dutré [13], the shape dependence was modeled and corrected, then being able to match the gloss appearance of two objects with different shapes.

The perceptual space is a remapping of the Ward BRDF model [15], which is defined by the following equation:

$$f(\omega_i, \omega_o, \alpha) = \frac{1}{\sqrt{(n \cdot \omega_i)(n \cdot \omega_o)}} \cdot \frac{e^{-\tan^2 \delta / \alpha^2}}{4\pi\alpha^2} \quad (5)$$

where ω_i and ω_o are the incident and outgoing light directions, respectively, n is the surface normal, δ is the angle between the surface normal and the half-way vector ($\frac{\omega_i + \omega_o}{2}$), and α is the Ward BRDF parameter that controls the width of the lobe.

A limitation of this work is that the space is only defined for the Ward BRDF model, thus limiting its applicability to materials defined by that model, and the fact that the perceptual uniformity was only valid for the materials used to create the space. In this paper the perceptual uniformity of the space is being evaluated.

Another perceptual space for gloss was introduced in Wills et al. [16]. In this case, 55 measured materials from the MERL database [8] were used to define the space. A two dimensional space was found by using multi dimensional scaling (MDS) to analyze the pairwise comparison by first estimating the dimensionality of the data, and then constructing the embedding space [1]. The main limitation of that space is the lack of perceptual axes, and the need to repeat part of the psychophysical experiment and rebuild the space every time a new material is added.

Experiments

Two experiments were performed in order to (1) Determine perceptual lightness differences in the *Lcd* space, and to (2) Evaluate the gloss uniformity of the *Lcd* space.

The method of constant stimuli was used together with a two-alternative forced choice (2AFC) design. Figure 1 shows the interface used in the different experiments, where two pairs of images were presented for each trial to the observers. The standard pair of images was on the left, and the test pair was on the right. The test pair was composed of a given gloss center and a test sample. The upper/lower position of the images for the test pair were randomized for each trial. The gloss center sequence and the test samples for each gloss center were randomized for each observer.

The question that the observers had to answer for each of the trials was the following one: *Which pair of images is more similar?*. Observers were instructed to judge the overall material appearance difference, i.e. taking into account both lightness and gloss differences. The left and right arrow keys on the keyboard were used to select the pair of images considered to be more similar. Twenty-one observers with normal color vision and normal or corrected to normal visual acuity participated in each experiment. The experiment was conducted in the dark and each observer performed a total of 1097 judgements for both experiments.

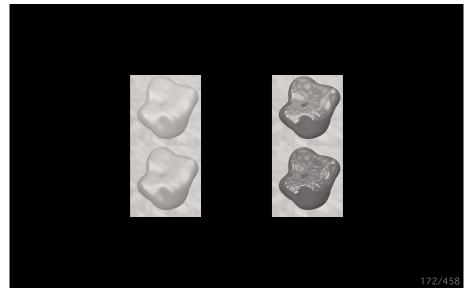

Figure 1. *User interface of the experiment developed with Psychtoolbox, showing the two pairs of images to be compared.*

In order to maximize the material discrimination in the experiment a blob-like shape and the Eucalyptus Grove light probe from Paul Debevec were used. This geometry gave the best material discrimination accuracy in Vangorp et al. [14] and this environment map was found to be the environment map with real world statistics providing the best material discrimination in Fleming et al. [3], respectively.

A 30-inch HP ZR30w display was used for the experiment and was characterized using a PR-655 spectroradiometer and the Day method [2]. A good display's additivity was observed, and a mean $CIEDE2000$ of 0.33 was found when displaying the colors of the 24 patches of the Macbeth Color Checker.

The Physically Based Ray Tracer (PBRT) [10] was used to generate the synthetic images presented to the observers. The pfstools framework [7] was used to apply the Reinhard et al. [12] global tone mapping operator (key$= 0.18$ and $\phi = 1.0$) to a tiled image containing all the images used for each experiment. Then, the resulting CIE Y was linearly mapped to the display's dynamic range. Next, the color for each pixel was set to be neutral by scaling its X and Z components: $X = Y \frac{X_{wp}}{Y_{wp}}$, $Z = Y \frac{Z_{wp}}{Y_{wp}}$, being XYZ_{wp} the display's white point. Finally, the inverse of the display model was used to convert from XYZ to display digital counts.

Experiment 1: Adding lightness to the space's distance metric

The goal of the first experiment is to add a function for L^* to the gloss distance measure seen in Equation 4.

The *Lcd* space difference equation presented in Pellacini et al. [9] does not define how the differences in lightness are related to differences in the other dimensions of the space, c and d. For that reason, differences between materials with different lightness can't be resolved using the current equation.

The experimental design explained in the previous section was used to understand and model the behavior of L^* in the *Lcd* space. The standard pair was defined to only vary in a single dimension ($d = \{0.9, 0.9281\}$), while having constant lightness and contrast ($L^* = 30$, $c = 0.25$). The distance between the standard pair was equal to $D_{i,j} = 0.05$ in the uniform space described in Equation 4.

Several gloss centers were studied to better understand the perception of lightness differences across the space. Five positions in the *cd* plane were selected to study if there was a lightness perception difference depending on the position on that plane ($cd = \{0.2, 0.85\}$, $\{0.3, 0.9\}$, $\{0.4, 0.95\}$, $\{0.1, 0.8\}$, $\{0.15, 0.925\}$). Then, a gloss center was defined at $L^* = \{10, 20, 40, 60, 80\}$ for each of the *cd* positions.

Eleven test samples were defined for each gloss center, varying only in L^*. They spanned the range $[L^* - 10, L^* + 10]$ with an interval of 2 when the gloss center was at $L^* = 10$, and the range of $[L^* - 20, L^* + 20]$ with an interval of 4 for gloss centers defined at other L^*. The materials described above that given its contrast (c) and lightness (L^*) would not enforce energy conservation were not evaluated.

Results Experiment 1

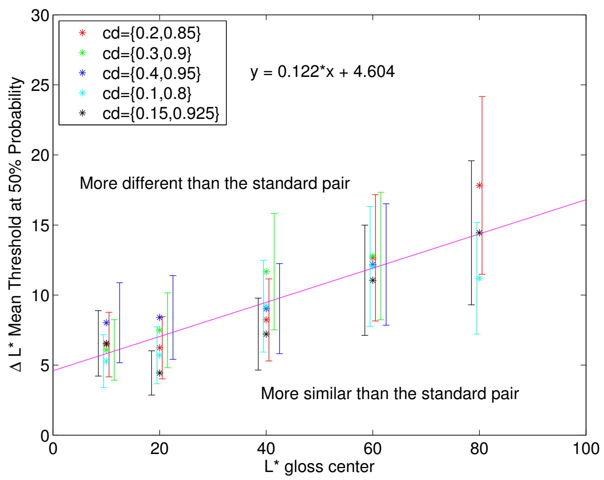

Figure 2. *L^* approximation function, being $D_{i,j} = 0.05$ the standard pair distance.*

For each test sample, the frequency of observers judging it to be closer to the gloss center than the standard pair was first calculated. Next, a gaussian function was fitted for each gloss center to the frequency of its test samples. The gaussian function was then used to obtain the lightness difference probability at 0.5, 0.75, and 0.25 from the gloss center, shown as $*$, lower, and upper error bars in Figure 2, respectively. The L^* perception was found to be independent of the *cd* position and the lightness differences were approximated with a linear function. Care should be taken when using the function outside the range studied $[10, 80]$.

The lighter the gloss center is, a greater change in lightness is needed for observers to perceive the test pair as more different than the standard pair. Meaning that the observers lightness discrimination decreases as lightness increases. Thus, the perception of lightness differences depends on the lightness of the samples.

The approximation obtained in Figure 2 can be used in the following form to compute the perceived lightness difference in the *Lcd* space:

$$f_L(L_i, L_j) = 0.05 \frac{|L_i - L_j|}{0.122\, L_i + 4.604} \qquad (6)$$

where the 0.05 is the distance $D_{i,j}$ of the standard pair (which corresponds to the magenta line in Figure 2). Note that in this case $f_L(L_i, L_j) \neq f_L(L_j, L_i)$ and care must be taken to use the gloss center as L_i. Another option is to use the mean ($\frac{L_i + L_j}{2}$) instead of L_i in the denominator to compute the distance in the point located in the middle of the two samples, thus obtaining a symmetric function.

The revised distance function once lightness is added to the *Lcd* space is the following:

$$\Delta Lcd = \sqrt{[c_i - c_j]^2 + [1.78(d_i - d_j)]^2 + f_L(L_i, L_j)^2} \qquad (7)$$

Discussion Experiment 1

In this gloss space L^* is used to define the material appearance of an object, and that appearance representation is later used to generate synthetic images. In this work, as in Pellacini et al. [9] where the original space was defined, a LDR display is used, which requires the tone mapping of the images before being displayed. Tone mapping operators mostly compress the luminance of the scene, and this compression is probably being represented in the function obtained in Figure 2.

As future research, it would be interesting to study if there is a relation between the lightness difference function and the tone mapping operator used. At the same time, if the *Lcd* space is to be used to judge the perceived gloss differences between real objects, a similar experiment to the one performed in this work should be performed using either real samples or a high dynamic range display, as it is known that limiting the image dynamic range does change the apparent gloss of surfaces depicted in images [11]. Another reason why a function is required for L^* might be related to the same need as in the CIEDE2000 color difference equation.

Experiment 2: Gloss uniformity validation

The goal of the second experiment is to validate the uniformity of the *Lcd* space presented in Pellacini et al. [9].

The positions 1-5 in Table 1 were used as gloss centers for this experiment. Those positions are the approximation of 5 materials of the MERL database [8] (pearl-paint, gold-paint, color-changing-paint3, nickel, and silver-metallic-paint) into the *Lcd* space using the projection defined in Fores et al. [4], and can be seen in Figure 3.

Only variations in the *cd* plane were considered for the test samples in order to evaluate the current weights of the *cd* dimensions in Equation 4. At the same time, the number of trials to perform was greatly reduced by only sampling two of the three dimensions of the *Lcd* space. To sample around each gloss center the Equation 4 was taken into account in order to have six perceptually equal steps in each dimension (step size $\Delta c = 0.033$ and $\Delta d = 0.033/1.78$) centered in the gloss center. Also, the gloss center itself was used as a test sample. As the test samples only varied in the *cd* plane, the standard pair for this experiment only varied in L^* and had $L^* = \{20, 15\}$ and $cd = \{0.2, 0.85\}$.

Results Experiment 2

The same idea of the MacAdam ellipses or color tolerances in CIELAB space will be used to evaluate the space uniformity. The gloss space will be uniform in a region if the difference of the standard pair to the test samples around the gloss center defines a circle, and the space will be non-uniform if an ellipse is obtained.

To compute each ellipse, the test samples that were selected by the observers to be more similar than the standard pair with

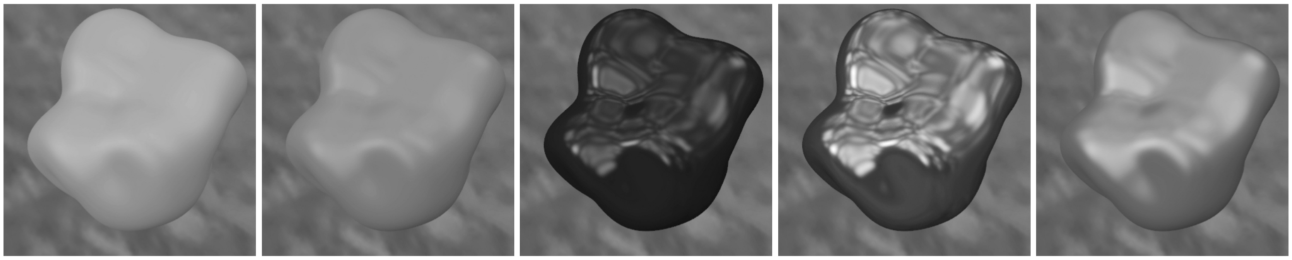

Figure 3. *Gloss Centers 1-5 used to evaluate the space uniformity.*

Gloss Center	L	c	d
1	53.23	0.1333	0.7772
2	43.44	0.099	0.8415
3	3.60	0.1567	0.9504
4	10.38	0.3969	0.9525
5	31.02	0.2878	0.8503
6	10.00	0.10	0.9
7	20.00	0.20	0.875
8	50.00	0.20	0.875
9	80.00	0.20	0.875
10	60.00	0.25	0.93
11	5.00	0.50	0.875
12	20.00	0.65	0.93
13	5.00	0.65	0.93
14	35.00	0.65	0.93
15	20.00	0.056	0.85
16	15.00	0.30	0.973

Table 1. Lcd coordinates of the gloss centers studied.

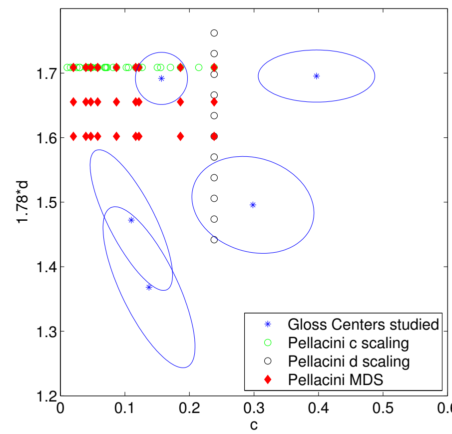

Figure 4. *Ellipses obtained from the 5 gloss centers, showing the non-uniformity of the space outside the samples used to create the gloss space in Pellacini et al. [9].*

a frequency of 0.5 or higher were first selected. Then, a covariance matrix was defined with those test samples. Finally, the 95% confidence interval ellipse was obtained for the given covariance matrix and sample mean. As the sampling was selected to be uniform in the gloss space, the test samples were equally spaced. The ellipses obtained for each gloss center and the samples used to create the space in Pellacini et al. [9] can be seen in Figure 4. In this case, the standard pair had a $\Delta Lcd = 0.036$ when using Equation 7.

Discussion Experiment 2

Circles would have been obtained instead of ellipses for each gloss center if the *cd* space was uniform. The ellipse determines the 95% confidence interval where 50% of the observers selected that the test pair was more similar than the standard pair.

Consequently the *Lcd* space defined in Pellacini et al. [9] is non-uniform for the gloss centers tested. It's interesting to note that the original distance metric of the space seen in Equation 4 is only perceptually uniform around the top left gloss center studied, while being non-uniform for the rest of the gloss centers evaluated. In fact, the top left gloss center studied is the only one located between the samples used to define the gloss space in Pellacini et al. [9] (see Figure 4). This finding agrees with the claim that the space only accurately predicts the appearance for materials in the range of the samples used to create the space, as stated by the authors [9].

From the small number of gloss centers evaluated in this experiment a trend can roughly be seen when looking at Figure 4. A compression in the *c* dimension might be needed with increasing *c*, as depicted by looking at the right-most ellipses. While a rotation and an additional compression in the *d* dimension for materials on the lower left quadrant might also be needed. It's also important to note that the different gloss centers have different lightness, as seen in Table 1, and lightness might also need to be considered when trying to improve the space uniformity.

Experiment 2.1: Sampling extra gloss centers

In this experiment the space uniformity around additional gloss centers throughout the space was evaluated. This experiment was designed to better understand the non-uniformity of the space found in the second experiment, to see if the same trends seen in Figure 4 are maintained, and to aid the development of an improved gloss difference equation.

Eleven new gloss centers (6-16 in Table 1) were defined across the space with the goal to better understand the non-uniformity of the space, to evaluate materials with higher contrast and the ones closer to the boundaries of the space ($c = 0$ and $d = 1$), and to evaluate some *cd* positions at different L^* planes to analyze the relation of lightness with the other dimensions of the space.

The space uniformity around two different *cd* positions was evaluated at three L^* planes (gloss centers $(7,8,9)$ and $(12,13,14)$ in Table 1). To maximize the lightness range studied the L^* planes evaluated for each *cd* position were different, as to enforce energy conservation materials with lower contrast (c) can reach higher lightness than high contrast materials.

The experiment procedure was the same performed in the second experiment. The only difference was the sampling rate used for the gloss centers closer to the boundaries (15 and 16), being 4x8 (*c x d*) for the gloss center closer to $c = 0$ and 8x4 for the sample closer to $d = 1$. The same step size used in the second experiment was used.

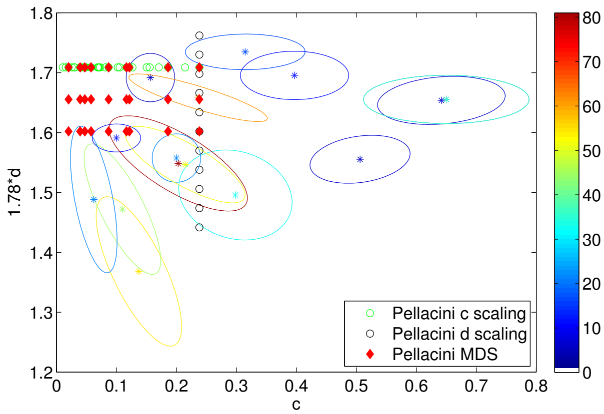

Figure 5. *Ellipses obtained from the 16 gloss centers showing the space non-uniformity and the original samples used to create the space in Pellacini et al. [9]. The ellipses are color-coded with its lightness plane.*

Results Experiment 2.1

The same procedure used to obtain the ellipses in the second experiment was performed for the new gloss centers evaluated. The ellipses obtained are shown in Figure 5 together with the original samples used to create the space in Pellacini et al. [9].

An increased elongation in the *cd* plane is observed as L^* increases, as can be seen in the two *cd* positions evaluated at three lightness planes. Only two of the three different gloss centers at the $cd = \{0.65, 0.93\}$ position can be seen in Figure 5. This happens because the same test samples were selected by the observers with a frequency higher than 50% for the gloss centers 12 and 14, thus resulting with the same overlapping ellipse. At the same time, all the test samples available across the *c* dimension were selected for those two samples, meaning that a probably even larger horizontal elongation is perceived.

Discussion Experiment 2.1

The addition of eleven new gloss centers to the evaluation of the space uniformity allowed to confirm the trend seen in the second experiment, where there seems to be an elongation in the *c* dimension with increasing *c*, an elongation on *d* as *d* increases, and the orientation of the ellipses points out that there might exist a rotation point.

The increased elongation in the *cd* plane seen as L^* increases indicates that the observer discrimination decreases as L^* increases. The same effect was seen in the first experiment, where the lightness discrimination also decreases with lightness. However, a more complex interaction between L^* and the *cd* dimensions is apparent from the results obtained, as the elongation is dependent on the *cd* position of the sample. For the samples in the $cd = \{0.2, 0.875\}$ position, the space goes from being uniform to show an increased elongation as L^* increases, and for the samples in the $cd = \{0.65, 0.93\}$ position the space is already stretched at low lightness and it stretches even more as L^* increases. It's interesting to note that ellipse size of the gloss center with lowest lightness ($L^* = 5$) with high contrast ($cd = \{0.65, 0.93\}$) has almost the same size as the ellipse with mid contrast ($L^* = 50$) in the low contrast region ($cd = \{0.2, 0.875\}$).

A further evaluation is probably needed to better understand and be able to model the *cd* dimensions dependence on L^*. At the same time, it would also be interesting to further validate the uniformity of the region where the samples used to create the space in Pellacini et al. [9] are located and in addition evaluate that region at multiple lightness planes.

Improved gloss difference equation

In this section an improved gloss difference equation will be derived using the results from the psychophysical experiments described above.

The standardized residual sum of squares (STRESS) metric, presented in Garcia et al. [5] and commonly used in the Color Science community to evaluate color difference equations, will be used to evaluate the performance of existing and developed gloss difference equations. STRESS values measure the deviation between visual differences (ΔV) and numerical differences (e.g. ΔE^*_{ab}), while at the same time allowing to make statistical inferences of two different equations.

For each gloss center, the distance from the perceived location of the gloss center in the space ($*$ in Figure 5) to each point that defines the ellipse represents an equal visual difference, as the ellipse represents the materials that would have the same distance to the gloss center as the distance between the samples in the standard pair. To compute STRESS, the data for all gloss centers is used and compared to a given numerical difference equation applied to each pair of samples in the space. Because of the resemblance to its expressions and for easy understanding, reference to the color difference equations will be used throughout the following explanation.

First, the euclidian distance metric in the *Lcd* space (ΔE^*_{cd}) was computed for the gloss centers and ellipses obtained in this work, giving a STRESS value of 44.27. Then, the STRESS value using the gloss difference equation derived by Pellacini et al. [9] (Equation 4), was computed and a STRESS of 39.76 was obtained. Lower STRESS values indicate a lower deviation between visual differences and numerical differences, meaning that an improvement was obtained by scaling the *d* dimension by 1.78.

Space Modeling

The development of the improved gloss difference equation was guided by the goal to model the elongation in the *c* and *d* dimensions, to model the rotation observed in the ellipses, and with the assumption that the space is uniform in the region where the samples used to create the space are located.

The starting point of the modeling process was Equation 4, as it is assumed that it provides a perceptual uniform space where the samples used in Pellacini et al. [9] are located.

The use of cylindrical coordinates was a natural evolution in color difference equations, where the distance from neutral and the rotation angle is used to describe Chroma and Hue in CIELAB, respectively. The same approach was used in this work to improve the gloss difference equation of the space. In this case, the rotation point is not as clearly defined, neither conceptually nor as a point in the space. Still, the orientation of most ellipses seems directed towards a point near the upper left limit of the space, $cd = \{0, 1.78\}$. As we haven't found a conceptual meaning for the distance and rotation from the rotation point in terms of gloss, the same nomenclature, Chroma and Hue, as in CIELAB will be used for clarity.

Two optimization processes were done to first find the rotation point of the space, and then to model the increased ellipse elongation seen in Figure 5 as the gloss centers are farther a part from the rotation point. For the first optimization process, the rotation point (cd) and the function for Chroma that will be described later were non-linearly optimized to minimize the STRESS value. The sixteen ellipses found experimentally were used and the rotation point obtained was $Rot_{cd} = \{0.004, 1.686\}$. The rotation point represents the point in the space that better aligns with the long axis of all the ellipses.

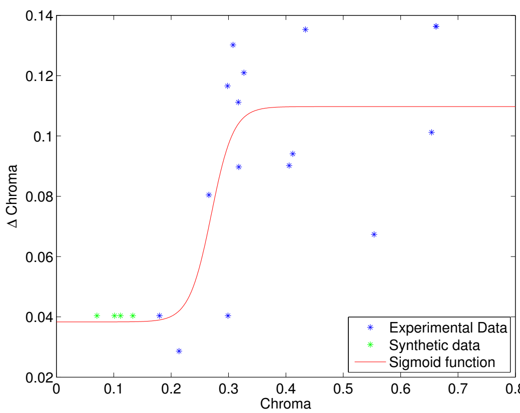

Figure 6. *Chroma vs ΔChroma for the 16 gloss centers obtained in our study, the four synthetic circles added to enforce the uniformity in the area where the Pellacini et al. [9] samples were located, and the sigmoid used to approximate the data.*

Once the rotation point was known, a second optimization process was performed to add a weighting function to Chroma. Chroma defines the distance from the rotation point and directly relates to the increased ellipse elongation as the gloss centers are farther a part from the rotation point. In this case, four synthetic circles equal in size to the top left circle seen in Figure 5 were placed in the region where the Pellacini et al. [9] samples are located in order to enforce the space uniformity in that area. That decision lead to the good performance of a sigmoid function, as can be seen in Figure 6. Chroma is the distance from the rotation point to the gloss center (see Equation 8), and Δ Chroma is the radius of the ellipse in the direction of the rotation point from the center of the ellipse. The four additional circles added and the sigmoid function that approximates both the experimental and synthetic data are also shown in Figure 6.

For the second optimization process, the parameters of the sigmoid function were non-linearly optimized to minimize the STRESS value. In this case, both the sixteen ellipses found experimentally and the four synthetic circles were used during the optimization process. The sigmoid parameters obtained were the following: $p = \{0.87, 2.66, 0.15, 3140.9\}$. Finally, the first parameter (p_1) was set to 1 in order to enforce the region uniformity where the Pellacini et al. [9] samples are located. A STRESS value of 22.96 was obtained when the sixteen ellipses found experimentally were evaluated, which was found to be a statistically significant improvement when compared to the ΔE^*_{cd} and the $D_{i,j}$ gloss difference equation from [9].

To compute the gloss difference equation the distance from the rotation point for each sample (Chroma) is first computed:

$$C_1 = \sqrt{[c_1 - Rot_c]^2 + [(1.78d_1) - Rot_d]^2} \quad (8)$$

$$C_2 = \sqrt{[c_2 - Rot_c]^2 + [(1.78d_2) - Rot_d]^2} \quad (9)$$

where the rotation point $Rot_{cd} = \{0.004, 1.686\}$, and cd are the coordinates of the two samples evaluated. Next, the Chroma and Hue differences between those samples are computed as in ΔE^*_{94}:

$$\Delta c = c_1 - c_2 \quad (10)$$

$$\Delta d = d_1 - d_2 \quad (11)$$

$$\Delta C_{cd} = C_1 - C_2 \quad (12)$$

$$\Delta H_{cd} = \sqrt{\Delta c^2 + \Delta d^2 - \Delta C_{cd}^2} \quad (13)$$

The sigmoid function used in Figure 6 is the following one:

$$S_C = p_1 + \frac{p_2 - p_1}{1 + 10^{[(p_3 - C_1)p_4]}} \quad (14)$$

where $p = \{1, 2.66, 0.15, 3140.9\}$ are the sigmoid parameters. Finally, the gloss difference equation is computed:

$$\Delta G^*_{cd}(Lcd_1, Lcd_2) = \sqrt{f_L(L_1, L_2)^2 + \left(\frac{\Delta C_{cd}}{S_C}\right)^2 + \Delta H_{cd}^2} \quad (15)$$

where Lcd_1 and Lcd_2 are the coordinates of the two samples, S_C is used to weight ΔC_{cd}, and Equation 6 is used to compute f_L.

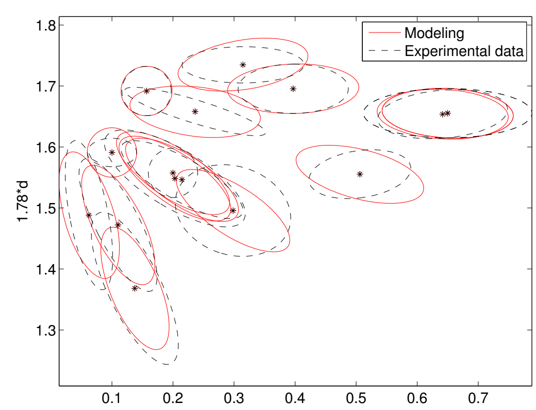

Figure 7. *Ellipses obtained in the psychophysical studies are visualized with dashed black lines, and results obtained using the gloss difference equation ΔG^*_{cd} developed are shown in red.*

The approximation of the experimental results with the derived gloss difference equation can be seen in Figure 7, where the resulting ellipses from the experiments are shown in dashed black lines, and the ellipses obtained with the ΔG^*_{cd} are shown in red. In order to compare the size and orientation, the same scaling used to match the experimental data of the top left circle with the gloss difference equation was used for all the other ellipses. As C and H are independent from L^*, the results seen for the gloss centers studied at three different lightness planes are not represented, and the same ellipse is obtained in each cd position.

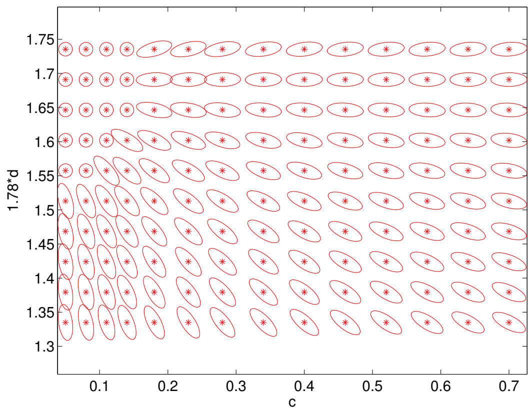

Figure 8. *Ellipses displayed across the* cd *plane in order to show the function behavior across the space. Note that the* cd *plane shown is independent of lightness.*

Figure 8 shows the behavior of the ΔG^*_{cd} at different locations across the cd plane at any L^* level. The space is uniform in the region where the samples used to create the space in Pellacini et al. [9] were located, while outside this region the ellipses are elongated in respect to the rotation point.

Conclusion and Future Work

Two experiments were performed in this paper. The first one was used to evaluate the lightness perception in relation to the contrast gloss and distinctness of image gloss dimensions of the space. The lightness discrimination was found to decrease as lightness increased. The lightness perception was then modeled and included into the distance metric of the gloss space.

The second experiment was used to evaluate the space's perceptual uniformity, finding that the space is only uniform in the region where the samples used to create the space in Pellacini et al. [9] are located. Then, the space non-uniformity was modeled and an improved gloss difference equation was defined. A more detailed analysis is needed to better understand how L^* effects the space uniformity of the cd plane, and for that reason this interaction was not included in the gloss difference equation presented. As a future work it will also be interesting to validate the uniformity of the gloss space at different lightness planes in the region where the samples used to create the space are located.

It's important to note that this gloss space might not be able to represent all real materials as the gloss space is a remapping of the Ward BRDF model, which has an implicit modeling of the increased reflectance towards grazing angles (Fresnel effect) and its distribution can not accurately represent certain real materials [6].

Finally, the perception of color in relation to the gloss space would be an interesting avenue of future work to obtain an overall material perception space including both perceptual attributes, color and gloss.

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