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The influences of shape, size and gloss on the perceived colour difference of 3D printed objects

MIN HUANG, [1] JIE PAN, [1] YU WANG, [1] YU LI, [1] XIAOXUE HU, [1] XIU LI, [1] DONGQING XIANG, [2] CAROLINE HEMINGRAY, [3] AND KAIDA XIAO [3],*

[1] *Printing and packaging engineering, Beijing Institute of Graphic Communication, Beijing, CHINA, 102600; huangmin@bigc.edu.cn*
[2] *Zhuhai Sailner 3D Technology Co., Ltd, Zhuhai, CHINA, 519000; 2783431772@qq.com*
[3] *School of Design, University of Leeds, Leeds, LS2 9JT, United Kingdom*
* *k.xiao1@leeds.ac.uk*

Abstract: In order to study the influence and mechanisms of colour differences using 3D-shaped objects, 440 pairs of 3D samples surrounding five CIE colour centers (grey, red, yellow, green and blue) with the variations of gloss, size, and shape were prepared by Sailner 3D colour printer and their colour differences were assessed by 26~45 observers using the grey scale method. The new colour difference data were used to investigate the parametric effects (gloss, 3D shape and size) on the perceived colour difference. Results indicate that, for 3D objects, high gloss and small size objects (2 cm) raise smaller visual colour differences than matte and large size objects (4 cm), and the visual colour difference of spheres is larger than that of the cone and cylinder sample pairs. The chromaticity ellipses indicated that the glossy samples with different shape will arouse fairly different visual perceptions, especially for sphere and cylinder samples.

1. Introduction

Three-dimensional (3D) printing, also known as additive manufacturing, allows objects to be built directly from digitally rendered models. 3D printing can reduce the amount of materials required for production, compared to traditional manufacturing techniques, and facilitate the prototyping and manufacturing of complex objects [1]. The technology has made the manufacturing industry more personalized and convenient. In recent years, with the application of new materials and technologies, the limitation of a single material and colour in 3D printing technology no longer exists, and multiple materials and colours can now be used to build 3D objects simultaneously. 3D full colour printing technology has also become a possibility and can be applied in many fields, such as graphic art, rapid prototyping, medicine, education and so on [2-5]. Therefore, the colour measurement and colour difference evaluation of 3D sample pairs are becoming more important in the process of colour control and colour reproduction [6].

Conventionally, colour difference evaluation and prediction are based on flat colour samples, such as the CIELAB [7], CIEDE2000 [8] formulas recommended by CIE (Commission Internationale de l'Éclairage) for industrial colour difference evaluation. Similarly, colour appearance models, CIECAM02- (LCD/ SCD/UCS)[9] and CAM16-(LCD/ SCD/ UCS) [10], are used to predict the colour difference of 2D colour samples. The development and validation of these formulas are usually based on visual data sets from 2D colours, such as printed matter, textiles, and self-illuminated colour samples.

Compared with 2D samples, the visual colour perception of 3D samples is more complicated, and may be affected by factors including the shape [11], the geometrical structure of the light field [12], translucency [5], gloss [13, 14] and shadow. When the surface of a 3D sample is illuminated, the uneven shape of the surface will reflect the light in different directions, resulting in different colour perceptions when viewed in different directions. The use of existing colour difference evaluation and prediction formulas to 3D sample pairs is therefore an important area of research which needs to be studied.

With above issues in concern, CIE Technical committee TC 8-17 was established to study "Methods for Evaluating Colour Difference between 3D Colour Objects" [15]. Jiang Lan et al. [16] conducted a study to evaluate the colour difference of 3D objects. 75 pairs of 3D sphere samples and 75 pairs of 2D flat samples were prepared and their colour differences were evaluated by 10 observers using the grey scale method. Ten colour difference formulas, including CIELAB, CMC, CIEDE2000, CIECAM02, DIN99, OSA, etc. were evaluated. The results indicated that the colour difference magnitude, light source, and 3D shape had more or less influences on the perceived colour differences, which will affect the performance of existing colour difference formulas. Most of data collected in this study relate to objects with large colour differences but with the same level of gloss, size and shape. There is therefore a need to collect a comprehensive colour difference data set for 3D objects which cover different parameters, including shape, size and gloss.

In this study, we prepared 440 pairs of 3D printed colour samples with three shapes (spheres, cones and cylinders), two sizes (4cm and 2cm) and two gloss level (matte and gloss). The colour difference experiments were conducted by 26-45 colour normal observers and 20710 colour difference data were collected. The influence of parametric effects on the perceived colour difference of 3D objects was analyzed comprehensively.

2. Experimental

2.1. Information of the experiments

According to different experimental samples and observation conditions, our experiment is divided into four phases, henceforth named EXP. I, EXP. II, EXP. III, and EXP. IV. Table 1 summarized the experimental information of the four data sets studied, the 3D sample pairs were prepared with different shapes, gloss and sizes, and also illuminated by different light sources. The four groups of experimental data sets were divided into eight phases according to the shape of the samples, named Sp-4-m, Sp-4-g, Sp-2-m, Co-4-m, Cy-4-m, Sp-2-g, Co-4-g, Cy-4-g, as shown in the column "Abbr." in Table 1. The combination of two letters in front of the short line represents the shape of the sample (Sp, Co, Cy is sphere, cone, cylinder respectively), and the numeral 4 or 2 represents the size of the sample is 4cm or 2cm, respectively, and m or g represent the sample surface is matte or glossy.

Table 1. The detailed information of the four groups of experiments

EXP.	Light sources	Shape	Abbr.	Property	Size	Sample pairs	CIELAB	$\overline{\Delta E}^*_{ab}$	Observers	Colour difference data (times×pairs)
I	L1	Sphere	Sp-4-m	Matte	4cm	150	0.80~12.71	5.04	33	43×150
II	L2	Sphere	Sp-4-g	Gloss	4cm	50	0.46~13.08	4.74	26	50×50
III	L3	Sphere	Sp-2-m	Matte	2cm	40	0.54~16.86	5.46	45	49×120
		Cone	Co-4-m		4cm	40		5.19		
		Cylinder	Cy-4-m		4cm	40		6.16		
IV	L2	Sphere	Sp-2-g	Gloss	2cm	40	0.66~13.46	5.09	35	49×120

Cone	Co-4-g	4cm	40	5.33
Cylinder	Cy-4-g	4cm	40	5.23

2.2. Light sources

The visual experiments were carried out in a dark room with the viewing cabinet. In EXP. I and EXP. III, the matte samples were illuminated by the directional light, which was equipped with a GretagMacbeth The Judge II viewing cabinet and named L1, L3 respectively. The samples were directly illuminated by light sources in the cabinet and light diffusely reflected in the walls of the cabinet. In EXP. II and EXP. IV, the gloss samples were illuminated by the diffused light, which was equipped with a spectrally tunable LED lighting system, provided by Thouslite Inc., China, named L2. The size of the GretagMacbeth The Judge II viewing cabinet is 67 cm (length) × 51cm (width) × 55cm (height) and the size of the spectrally tunable LED lighting system is 50 cm (length) × 50cm (width) × 60cm (height), the samples were placed in the middle of the cabinet. The colorimetric values of the background of GretagMacbeth The Judge II and LED lighting system measured by the X-Rite Ci64 spectrophotometer with the condition of D65/10° were L^*_{10}=64.18， a^*_{10}=0.15， b^*_{10}=2.12; L^*_{10}=71.69， a^*_{10}=-0.74， b^*_{10}=1.50 respectively. The relative spectral power distributions (SPDs) of L1, L2 and L3 were measured at the position of the samples using the Photo-Research PR655 spectroradiometer, and the results are shown in Fig. 1.The illuminance at the position of the samples for the three light sources of L1~L3 were 878lx, 1052lx and 890lx, the correlated colour temperatures (CCT) were 6253K, 6492K, 6344K, and the CIE colour rendering indices (CRI) [17]of 93.3, 96.9, and 92.1 respectively, which was measured by Handheld illuminance meter UPRtek MK350N.

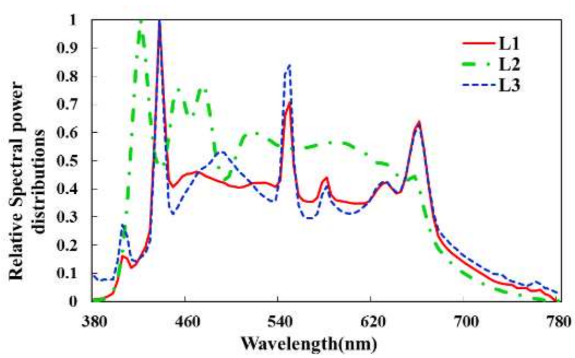


Fig. 1. Relative spectral power distributions (SPDs) of the three light sources

2.3. Sample preparation

In this study, the 3D samples were printed by Sailner J400 and J501 3D colour printers provided by Sailner 3D Technology Co., Ltd, Zhuhai, China with the optical property of matte and gloss. The principle of the 3D printers in this study is similar to those of 2D inkjet printer, which contains four primary colours, such as cyan, magenta, yellow, black, and an additional white colour was added to adjust the lightness of the printed samples. The print head prints a thin layer of photosensitive resin each time, and then it is quickly cured with ultraviolet light. When the printer finishes printing one layer, the forming tray of the machine descends to print the next layer. All the printed samples are matte, and in the post-processing, some samples were selected and varnished for polishing as glossy samples. Considering the operability of gloss measurement, the flat samples which had the same gloss as the 3D samples were selected. The values were 3.6 GU and 96.6 GU for matte and glossy samples by GLOSS METER TC-108DPA provided by TOKYO DENSHOKU Co. Ltd., Japan, with the angle of 60°. Specifically, three different shapes, sphere, cone and cylinder were prepared with the size of

4cm and 2cm respectively. The dimensional definition of the samples are as follows, the diameter of the sphere were 4cm, the bottom diameter and height of the cone and cylinder were both 4cm. For the 2 cm sized samples, the diameter of the sphere was 2cm. Fig. 2 shows the view of the samples. All the samples were prepared surrounding the CIE five colour centers[18] (grey, red, yellow, green, and blue), which were recommended by the CIE for evaluating the uniformity of colour space and the performance of colour difference formulas. In the experiments, the samples were prepared carefully and the 440 samples were selected from thousands of samples with different ΔE^*_{ab} colour difference magnitudes.

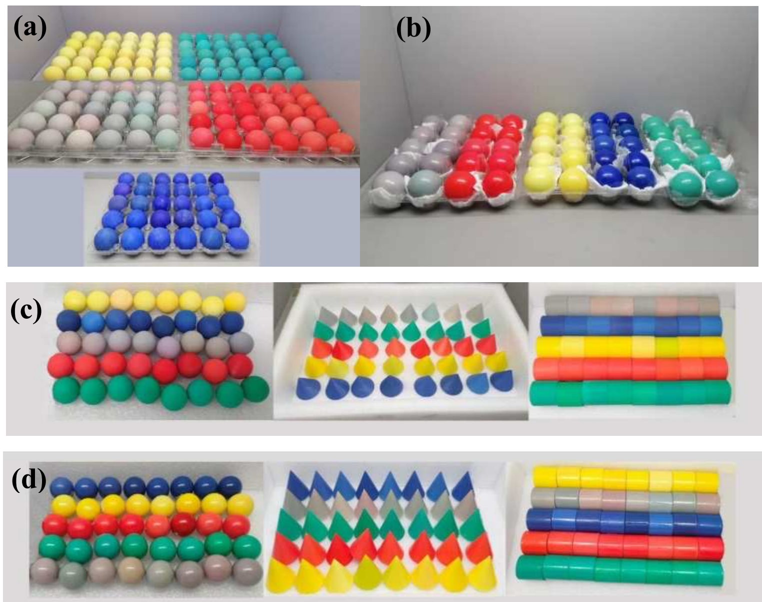


Fig. 2. Appearance of experimental 3D samples (a) EXP.I (b) EXP.II (c) EXP.III (d) EXP. IV

2.4 Colour measurement

Due to the limited uniformity of 3D samples in the production process, the surface of the samples with uniform colour were carefully selected and used as the observation region in the psychophysical experiment. In colour measurement, five points on the observation region were randomly selected and measured by the X-Rite Ci64 spectrophotometer, and then the averaged values were used to represent the final values of the 3D samples. The uniformity of the samples was characterized using the *MCDM* (Mean Colour Difference from the Mean) [19] values in the CIE 1976 $L^*a^*b^*$ colour space with the condition of D65/10°, as shown in equation (1).

$$MCDM = \frac{\sum_{i=1,N}[f_{\Delta E}(C_i, C_{ave})]}{N} \quad (1)$$

where N =5, indicates the number of the measurements, C_i is the $L^*a^*b^*$ values of the i^{th} (i=1~5) measurement, C_{ave} is the average $L^*a^*b^*$ values of the N measurements, and $f_{\Delta E}$ is a function to calculate colour differences such as ΔE^*_{ab}. The mean *MCDM* values of the samples in EXP. I to EXP. IV were 1.4, 1.5, 1.5 and 1.3 ΔE^*_{ab} units, respectively, and the maximum *MCDM* values of the samples in EXP. I to EXP. IV were 3.8, 2.9, 3.8, 4.6 $\Delta E^*_{ab,10}$ units, respectively. It means that the uniformity of the sample meets the experimental requirements.

The spectral reflectance of all 3D samples were measured by the X-Rite Ci64 spectrophotometer with the mode of SPIN and the colorimetric values were calculated based on different light sources and CIE 1964 10° colour matching functions in the following work. As mentioned in Table 1, the CIELAB colour differences of the 440 sample pairs in EXP. I to

EXP. IV were ranging from 0.46~16.86, which included threshold colour difference (TCD), small colour difference (SCD) and large colour difference (LCD). Further, we divided these colour differences into different magnitudes, Fig. 3 shows the number of samples belonging to different CIELAB colour difference ($\Delta E^*_{ab,10}$) magnitudes. There are 26.8%, 27.5%, 25.2% and 13.9% sample pairs in 0.0~3.0, 3.0~5.0, 5.0~8.0 and 8.0~10.0 colour difference magnitudes respectively. In the preparation of the 3D samples, it is very difficult to make sure that the colour difference was only or mainly from ΔL^*_{10}, ΔC^*_{10} and ΔH^*_{10}. The weight effects of different parameters are similar in most samples. For example, the distributions of colour differences in Δa^*_{10} Δb^*_{10} and ΔL^*_{10} $\Delta C^*_{ab,10}$ for yellow center in EXP. I are shown in Fig. 4.

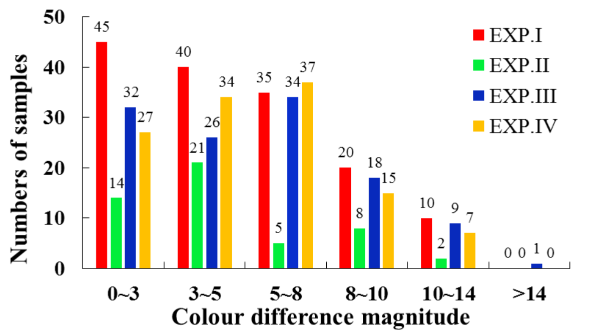


Fig. 3. The numbers of samples in different colour difference magnitudes

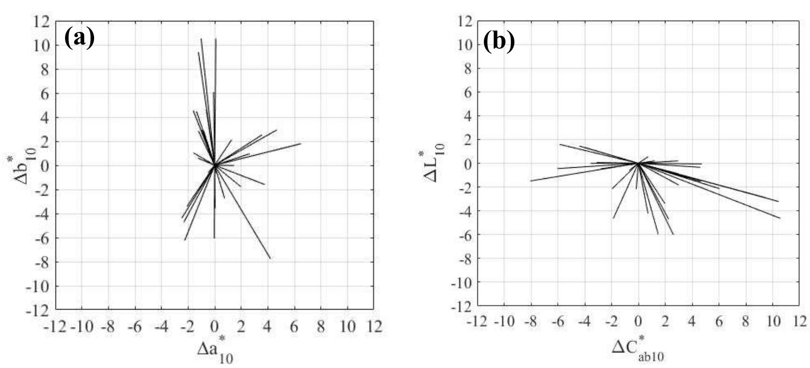


Fig. 4. The distributions of colour differences in CIELAB (a) Δa^*_{10} Δb^*_{10} and (b) ΔL^*_{10} $\Delta C^*_{ab,10}$ for Yellow center in EXP. I

2.5 Grey Scale

The grey scale method[20] was used to evaluate the colour difference of the sample pairs, as shown in Fig. 5. Our grey scales had colour difference grades from 1 to 14 and were printed by an Epson Stylus PRO 7908 inkjet printer on the substrate of semi-gloss paper (with the gloss of 36.1) respectively. The printed grey scales were attached to a black matte card with the $L^*_{10}a^*_{10}b^*_{10}$ values of 33.31, -0.6, -0.64. Considering the accuracy of the grey scale, we used four grey scales numbered No.1-No.4 (used in EXP. I-IV) in different time periods, and the linear relationship between their grades (GS) and colour difference value $\Delta E^*_{ab,10}$, as well as the goodness of fit R^2, are shown in equations (2) - (5), which represent the grey scale fitting results of EXP. I-IV, respectively.

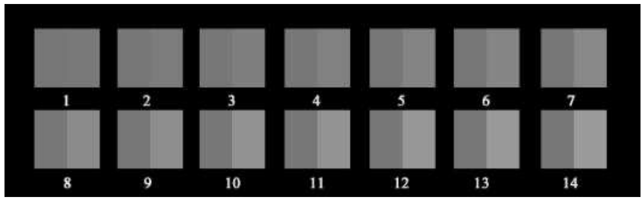


Fig. 5. The grey-scale used in the EXP.I

$$\text{EXP. I:}\quad \Delta E^{*}_{ab,10(1)} = 0.9577 \times Grade + 0.3031 \qquad (R^2=0.999) \qquad (2)$$

$$\text{EXP. II:}\quad \Delta E^{*}_{ab,10(2)} = 0.9958 \times Grade - 0.0199 \qquad (R^2=0.997) \qquad (3)$$

$$\text{EXP. III:}\quad \Delta E^{*}_{ab,10(3)} = 0.9413 \times Grade + 0.4669 \qquad (R^2=0.997) \qquad (4)$$

$$\text{EXP. IV:}\quad \Delta E^{*}_{ab,10(4)} = 0.8688 \times Grade + 0.1668 \qquad (R^2=0.997) \qquad (5)$$

2.6 Visual Experiment

During the visual evaluation experiment, each sample pair was placed with no gap and in the front of the grey scale in the viewing cabinet (see Fig. 6). The circular face of the cone was placed downward, and the cylinders were horizontally placed as shown in Fig. 2. The observers viewed the sample pairs with a distance of 40 cm, the field of view formed by a pair of sphere (4cm) or cone (4cm) or cylinder (4cm) was 11.4°×5.7°, and the field of view formed by a pair of sphere (2cm) was 5.7°×2.9°. The observers were trained on the grey scale method of colour difference evaluation before the formal experiment. The observer refers to the colour difference between the grey scales to judge the colour differences of the 3D samples (it is recommended that the visual colour difference given by the observer is kept to one decimal place). Before the beginning of the visual experiments, the light sources were warmed up for at least 15 minutes. Each observer viewed the viewing cabinet for one minute for fully chromatic adaptation.

Fig. 6. Diagram of visual assessment experiment

In EXP. I-EXP. IV, 26-45 human observers (16 males and 29 females) aged from 19 to 26 (mean = 20.5±1.44) were organized to participate in the visual experiments. All the observers had normal colour vision, passing the Ishihara Colour Vision Test, and they had participated in similar colour difference experiments before. In order to evaluate the repeatability of the observers, 4-24 observers carried out 2-3 repeated assessments. In total, 20710 (=43×150+50×50+49×40×3+49×40×3) colour difference data were collected in this study. It should be mentioned that the printed samples were composed of broad-band primary color spectrum and the colour rendering indices (CRI) of the three light sources were all above than 92.1, some supplementary visual experiments on some matte samples in L2 light source were conducted and the results indicated that three light sources have little effect on the experimental results.

3. Results and Analysis

3.1 Observer variability

Observer variability includes intra-observer and inter-observer variations, which are evaluated by the *STRESS* (Standardized Residual Sum of Squares) index[21, 22]. Intra-observer refers to the difference between each judgment and the average judgments of the observer, and inter-observer refers to the difference between each observer's average judgment and the average of all observers. The *STRESS* values for intra-observer and inter-observer variability in each experiment are listed in Table 2.

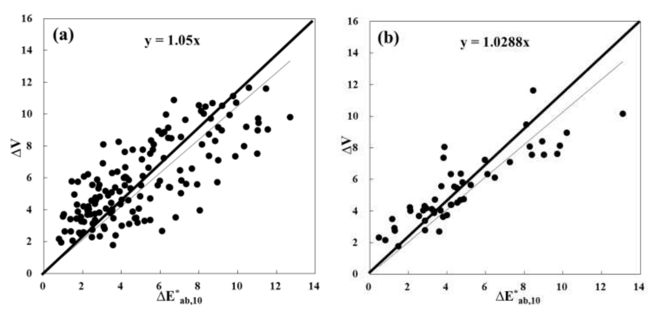
Table 2. Intra-observer and inter-observer variability in terms of *STRESS* in EXP. I~ EXP. IV

Observer	EXP. I		EXP. II		EXP. III		EXP. IV	
	Intra-	Inter-	Intra-	Inter-	Intra-	Inter-	Intra-	Inter-
Max	37.0	55.4	36.8	45.9	19.7	47.2	22.9	51.0
Min	12.4	21.9	10.8	19.5	13.8	19.0	17.7	19.4
Mean	21.9	31.2	20.0	30.3	16.7	30.4	20.1	30.8

In different phases, the main differences are light source and gloss difference. The *STRESS* of intra-observer, as well as the inter-observer in different experiments, is very similar. The results indicate that the parametric effect on observer variability of colour difference experiment was relatively small. Compared with similar previous studies[23, 24], the observer viability results are within a reasonable range, indicating the experimental data collected in this study is reasonable.

3.2 Colour Difference Data

For each pair of colour samples, the colour differences assessed by different observers under different repetitions were averaged respectively to represent overall visual results. The grey-scale grade (GS) was then used to covert mean observer results to visual colour difference value (ΔV) using the linear transform (equations 2-5). Fig. 7 (a)-(h) shows the scatter distributions of observer visual colour differences (ΔV) and device measured CIELAB colour differences ($\Delta E^*_{ab,10}$) of eight phases (Sp-4-m, Sp-4-g, Sp-2-m, Co-4-m, Cy-4-m, Sp-2-g, Co-4-g, Cy-4-g) in the Exp. I-Exp. IV. The linear relationship between ΔV and $\Delta E^*_{ab,10}$ for each phase is further fitted.



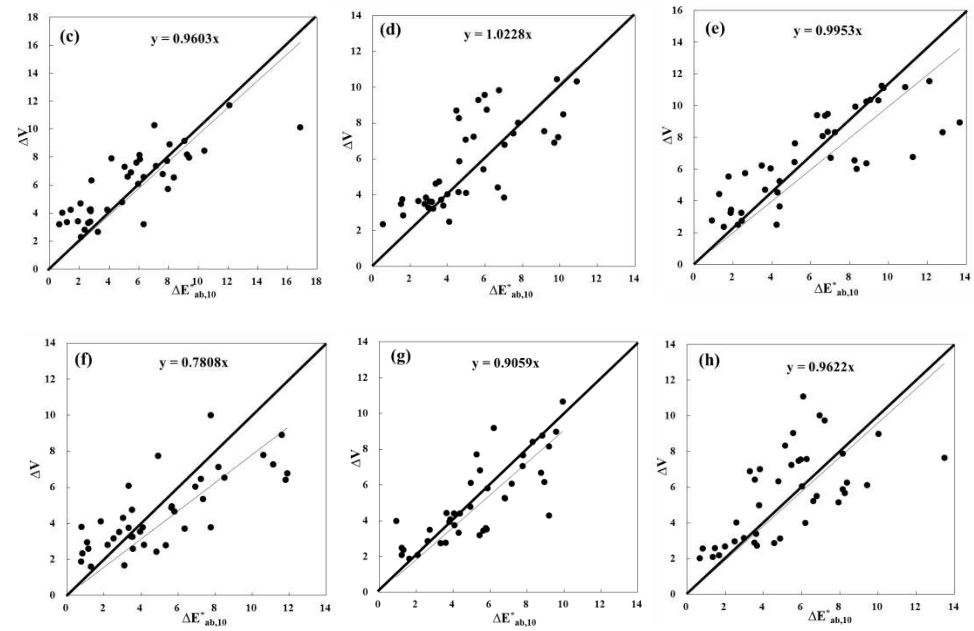


Fig. 7. Visual results (ΔV) plotted against $\Delta E^*_{ab,10}$ in each phase: (a) Sp-4-m; (b) Sp-4-g; (c) Sp-2-m;(d) Co-4-m;(e) Cy-4-m;(f) Sp-2-g ; (g) Co-4-g; (h) Cy-4-g.

The average visual values ($\overline{\Delta V}$) and average CIELAB values ($\overline{\Delta E}^*_{ab,10}$) for each part were calculated. The results are divided into two categories according to matte and glossy samples and given in Table 3. $\overline{\Delta V}/\overline{\Delta E}^*_{ab,10}$ is also displayed in the last column of Table 3. The difference in visual colour difference of different sample sets, that is the parameters, can be characterized by comparing the value of $\overline{\Delta V}/\overline{\Delta E}^*_{ab,10}$.

Table 3. The average $\overline{\Delta V}$, $\overline{\Delta E}^*_{ab,10}$ and $\overline{\Delta V}/\overline{\Delta E}^*_{ab,10}$ for each phase

Data	Matte			Data	Gloss			Mean
	$\overline{\Delta V}$	$\overline{\Delta E}^*_{ab,10}$	$\overline{\Delta V}/\overline{\Delta E}^*_{ab,10}$		$\overline{\Delta V}$	$\overline{\Delta E}^*_{ab,10}$	$\overline{\Delta V}/\overline{\Delta E}^*_{ab,10}$	
Sp-4-m	5.88	5.04	1.17	Sp-4-g	5.41	4.74	1.14	1.16
Sp-2-m	6.07	5.46	1.11	Sp-2-g	4.56	5.09	0.90	1.00
Co-4-m	5.75	5.19	1.11	Co-4-g	5.07	5.33	0.95	1.03
Cy-4-m	6.79	6.16	1.10	Cy-4-g	5.59	5.23	1.07	1.09
Mean	/	/	1.12	Mean	/	/	1.02	/

It can be seen that the $\overline{\Delta V}/\overline{\Delta E}^*_{ab,10}$ of the matte samples (with the value of 1.12) is larger than that of the gloss samples (with the value of 1.02), that is, the visual colour differences from the matte samples are larger than those of the gloss samples when they had the same colour difference. The samples used in the four parts in each column have different shapes or sizes and the $\overline{\Delta V}/\overline{\Delta E}^*_{ab,10}$ value of Sp-4-m and Sp-4-g are larger than other phases. We can preliminarily conclude that the sphere has a larger visual colour difference than the values from cone and cylinder sample pairs, and the visual colour differences of a 4cm sphere (Sp-4-m and Sp-4-g) are larger than those of a 2cm sphere (Sp-2-m and Sp-2-g).

In the following work, the visual colour differences and the chromaticity ellipses are used to further investigate the parametric effects on perceived colour difference.

3.3 Parametric Effect

3.3.1. Effect of gloss

The data sets in the four experiments were divided into two types based on their optical properties, such as matte and gloss. The matte datasets in EXP. I and EXP. III, and the gloss datasets in EXP. II and EXP. IV were analyzed.

In Fig. 8, it can be concluded that the visual colour differences of 3D matte sample pairs, are always greater than that of gloss sample pairs when they have similar calculated colour differences $\Delta E^*_{ab,10}$. In order to quantify the difference in visual colour difference of two datasets, the percentage of difference between two datasets is analyzed using equation (6).

$$P = \left(k_1 / k_2 - 1\right) \times 100\% \qquad (6)$$

where k_1 and k_2 means the slopes of the fitting lines by the two datasets.

It can be calculated from equation (6) that the visual colour difference of the matte samples increased by 10.9% compared to gloss samples. The results indicate that human perception is more sensitive to the colour difference of matte sample pairs, and that 3D gloss sample pairs will bring less colour difference perception. Higher lightness and saturation of the gloss objects may have impacted the human perception of their colour difference, more than that of matte objects, with human perception being more sensitive to sample pairs with low lightness and saturation.

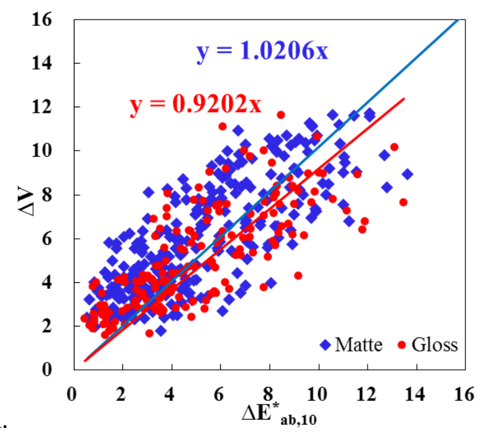


Fig. 8. Comparations of visual colour differences ΔV and computed colour differences $\Delta E^*_{ab,10}$ from sample pairs with different gloss

3.3.2. Effect of shape and size

The data sets from the sample pairs with different shapes but the same size is summarized in Fig. 9. In order to exclude the effect of gloss, Fig. 9 is divided into matte and gloss sample sets, as shown in Fig. 9(a) and Fig. 9(b). Similarly, the data sets of samples with the same shape but different sizes are summarized in Fig. 10, according to the properties of matte and gloss, see Fig. 10(a) and Fig. 10(b).

We can conclude that the sphere samples will arouse larger visual colour difference compared with cone and cylinder samples with the same gloss, and the visual colour difference of a 4cm sphere is greater than that of a 2cm sphere. In the matte and glossy sample sets, the visual colour differences for spheres increased 2.7% and 13.6% with respect to the values found for cone, and increased to 5.5% and 6.9% with respect to values found for cylinder respectively. In addition, in the matte and glossy sample sets the visual colour differences for spheres of 4 cm increased 9.3% and 31.8% with respect to values found for spheres of 2 cm. These results were obtained using equation (6) and may be due to the surface of the sphere being more regular than that of the cone and cylinder. When the observers evaluated the colour difference of the sphere sample pair, their attention was more focused, leading to obvious colour difference perception on the surface of sphere samples. In addition, when the observers are looking at a pair of spheres of 4cm and 2cm, the fields of view for each sample are 11.4°×5.7° and 5.7°×2.9° respectively. In general, large visual fields allow better colour discrimination than fields covering only the foveal region[25]. Moreover, as reported in a previous work using random-dot simulated textures[26], visual color differences decreased with increasing density of textures. From the point of view of color differences, non-uniform colors produced by lighting of 3D samples may lead to a similar visual effect to the one produced by mentioned random dots.

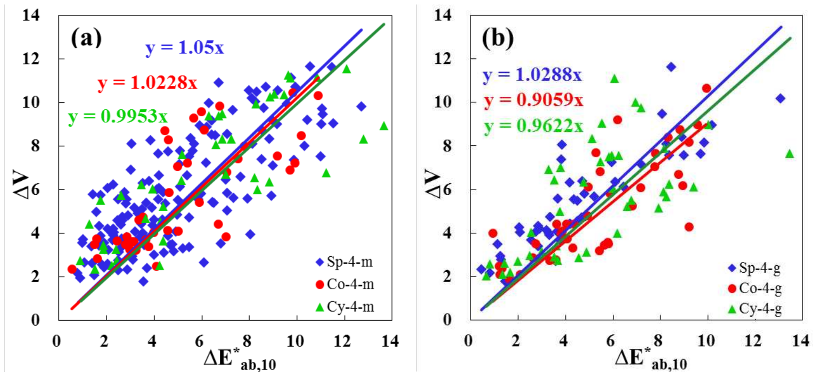


Fig. 9. Comparations of visual colour differences ΔV and computed colour differences $\Delta E^*_{ab,10}$ from sample pairs with different shapes (a)Matte (b)Gloss

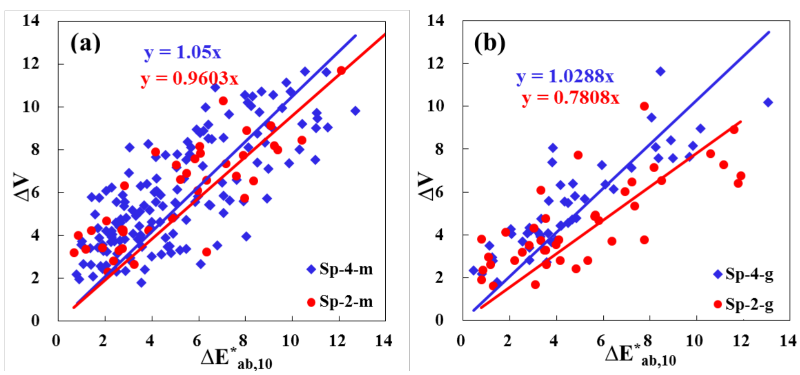


Fig. 10. Comparations of visual colour differences ΔV and computed colour differences $\Delta E^*_{ab,10}$ from sample pairs with different size (a)Matte (b)Gloss

3.3.3 Effect of colour difference magnitudes

At the same time, the sample pairs were divided into two parts according to their CIELAB colour difference magnitudes, such as SCD and LCD. Fig. 11_shows the results of different colour difference magnitudes where SCD means sample pairs have small colour differences ($\Delta E^*_{ab,10}$<5.0) and LCD means samples pairs have large colour differences ($\Delta E^*_{ab,10}$>5.0) in this paper. Two mathematical regression relations, including linear and power exponential regressions, were used to study the relationship between the computed colour differences $\Delta E^*_{ab,10}$ and visual colour differences ΔV.

With the increasing of $\Delta E^*_{ab,10}$, especially when $\Delta E^*_{ab,10}$ was larger than 5.0, the ΔV reported by observers tended to decrease gradually. The regression results are quite similar to those from the 2D sample pairs[27, 28]. In the visual experiments involving small colour differences, observers had difficulty in scaling colour differences, and they tended to avoid ΔV values which were close to zero reporting overestimated ΔV values[29]. On the other hand, it is also known that the visual estimations in the range from moderate to large colour differences tend to be slightly asymptotic[30].

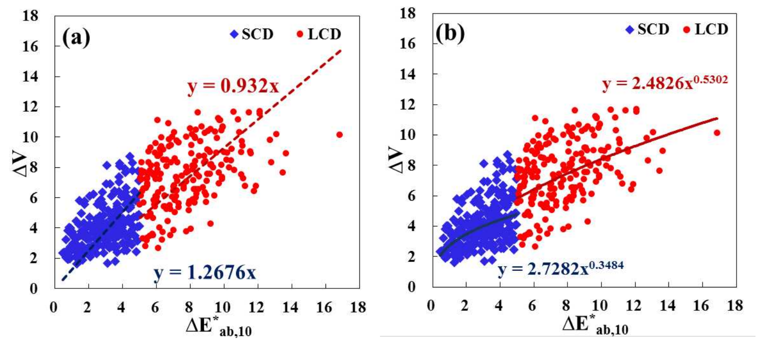


Fig. 11. Comparations of visual colour differences ΔV and computed colour differences $\Delta E^*_{ab,10}$ from sample pairs with different colour difference magnitudes (a)linear relationship (b)power function relationship

3.4 Chromaticity Discrimination Ellipses

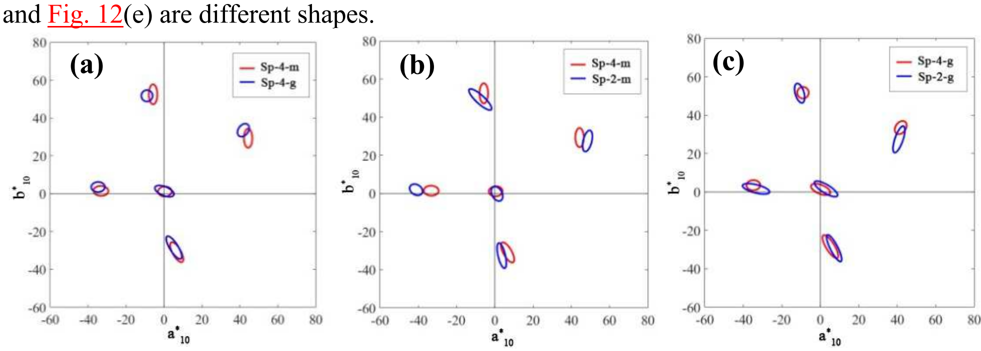
3.4.1 Chromaticity ellipses in this study

The degree of the influences of different parameters on the visual colour difference can be quantified by the chromaticity ellipsoids and ellipses, which can be calculated in CIELAB colour space for visualization of experimental data. The ellipsoid equation in equation (7) was used to fit experimental results for each colour center.

$$\Delta E^{*\,2}_{ab,10} = b_{11}\Delta a^{*2} + 2b_{12}\Delta a^*\Delta b^* + b_{22}\Delta b^{*2} + b_{33}\Delta L^{*2} + 2b_{13}\Delta a^*\Delta L^* + 2b_{23}\Delta b^*\Delta L^* \quad (7)$$

where ΔL^*, Δa^*, Δb^* are the lightness and colorimetric differences between the standard and compared samples, b_{ij} is the coefficients of the ellipsoid and used to be optimized to give the minimum *STRESS* value between the computed colour difference ΔE and the visual colour difference ΔV for each colour center. In equation (7) , the terms with $\Delta a^*\Delta L^*$ and $\Delta b^*\Delta L^*$ were disregarded because it was previously reported that they have very small effect on the simulated results[31], setting ΔL^* to zero allows the corresponding ellipse to be calculated in CIELAB $a^*_{10}b^*_{10}$ plane[16]. Thus, the optimization was done in MATLAB with the function of *fminunc* to obtain the coefficients b_{11}, b_{12}, b_{22} for each colour center.

The properties of the ellipses from different parts can reveal the influences of different parameters on the visual colour difference, especially the size of the ellipses can reflect the colour difference tolerance in each colour region. The eight sets of experimental data mentioned in Table 1 are drawn into the chromaticity ellipses according to different parameters of the experimental results, as shown in Fig. 12. The parameter variables of the data series in Fig. 12(a) are gloss and matte, in Fig. 12(b) and Fig. 12(c) are different sizes, and those in Fig. 12(d) and Fig. 12(e) are different shapes.



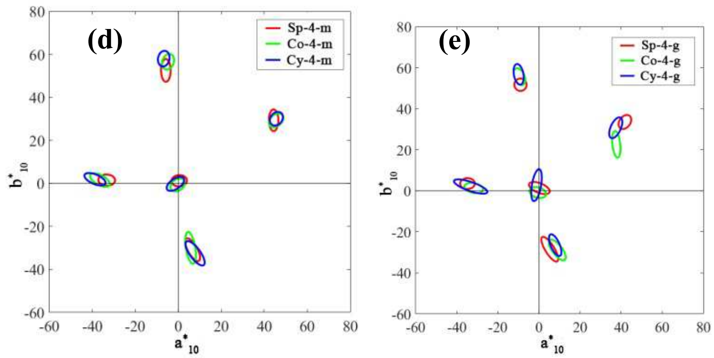


Fig. 12. Chromaticity ellipses are grouped and compared according to different parameters (a)spheres with different gloss (b) matte samples with different size (c) gloss samples with different size (d) matte samples with different shapes (e) gloss samples with different shapes

The parameters for each ellipse in different phases, in terms of semi-major axis(A), semi-minor axis (B), orientation angle(θ), the size of ellipse(S) calculated from ellipse area(πAB), are summarized in Table 4.

Table 4. Chromaticity ellipses parameters for different phases

EXP.		A	B	θ	S	EXP.	A	B	θ	S
Sp-4-m	grey	1.20	0.88	3.01	3.31	Cy-4-m	1.56	0.78	34.37	3.80
	red	1.68	0.74	90.4	3.88		1.16	0.90	50.27	3.28
	yellow	1.76	0.75	90.19	4.12		1.22	0.89	78.44	3.39
	green	1.30	0.87	177.63	3.53		1.75	0.74	156.95	4.08
	blue	1.98	0.73	119.22	4.54		2.27	0.81	126.23	5.81
	$\bar{S}$				3.88	$\bar{S}$				4.04
Sp-4-g	grey	1.78	0.78	157.90	4.37	Sp-2-g	1.36	0.88	118.66	3.76
	red	1.26	0.88	53.65	3.50		1.90	0.75	76.41	4.45
	yellow	1.01	0.99	87.64	3.13		2.60	0.74	137.46	6.00
	green	1.19	0.88	1.46	3.31		1.20	0.89	149.07	3.35
	blue	2.32	0.73	121.78	5.34		2.26	0.64	103.18	4.49
$\bar{S}$					3.88	$\bar{S}$				4.37
Sp-2-m	grey	1.36	0.88	118.66	3.76	Co-4-g	1.38	0.84	164.40	3.61
	red	1.90	0.75	76.41	4.45		2.18	0.64	96.13	4.37
	yellow	2.60	0.74	137.46	6.00		1.45	0.82	113.44	3.72
	green	1.20	0.89	149.07	3.35		1.53	0.79	168.88	3.80
	blue	2.26	0.64	103.18	4.49		2.02	0.79	127.34	5.06
$\bar{S}$					4.37	$\bar{S}$				4.08
Co-4-m	grey	1.22	0.88	33.75	3.35	Cy-4-g	2.62	0.74	80.30	6.10
	red	1.29	0.87	41.05	3.53		1.83	0.82	65.63	4.71
	yellow	1.24	0.88	70.96	3.42		1.70	0.77	100.47	4.12
	green	1.69	0.77	151.46	4.08		2.86	0.73	161.02	6.55
	blue	2.50	0.72	99.31	5.66		1.91	0.71	113.66	4.24

$\bar{S}$	3.96	$\bar{S}$	5.11

The estimation accuracy was evaluated by the *STRESS* value between the calculated $\Delta E^*_{ab,10}$ values from equation (7) and the visual colour differences from the visual experiments. The values were ranging from 5.67 to 40.61, with the mean of 22.16. Compared with the previous studies, the ellipses for 2D samples, such as the RIT–DuPont data from glossy paint samples reported in reference [32] and [33]; the BFD dataset, relating to small to medium colour differences of the surface colours including textile, paint, ink samples and BIGC datasets from matte and gloss printed samples reported in reference [33] and [34], were quite similar with those for 3D samples in each colour center, considering the shape, the orientation and the size. From Fig. 12 and Table 4, the ellipses for each colour region in different phases have different shapes, sizes and orientations, which maybe aroused by different parameters in the experiments. In total, the average size $\bar{S}$ of the five ellipses in each part was used to investigate the influences of the parameters, such as gloss, size and shape on the visual colour difference perception, with the values ranging from 3.88 to 5.11. In Sp-4-m and Sp-4-g, the values were both 3.88, and the value were 4.04 and 5.11 in Cy-4-m and Cy-4-g, which indicated that human perception is more sensitive to the colour difference from the sphere sample pairs and more tolerant to the glossy cylinder sample pairs. Meanwhile, in Sp-2-m, the average size of the five ellipses is 4.37, larger than that from Sp-4-m, indicating that the 2cm size of the sphere sample pairs will arouse less visual colour difference than that of 4cm size. Similarly, Sp-4-g and Sp-2-g also support this conclusion. In summary, the results in Table 4 supported the conclusions from Section. 3, indicating that the matte sphere sample pairs with 4cm size will arouse larger visual colour differences.

Moreover, a quantitative comparison between the ellipses of the present four phases was carried out using the Monte Carlo method developed by Strocka et al.[35], where the $\Delta E^*_{ab,10}$ values from two ellipse's equations using 1000 pairs of randomly generated colour samples were compared using the *STRESS* index. The results are given in Table 5 for different phases. The average variation using this method was 19.3 *STRESS* units for the five colour centers, where the blue center has the best consistency and the grey center has the worst consistency.

Table 5. Comparison of the present results with different phases in terms of *STRESS* using the ellipse-equation.

	1st Data	2st Data	Grey	Red	Yellow	Green	Blue	Average	Variables
(a)	Sp-4-m	Sp-4-g	20.3	24.5	26.0	3.89	3.83	15.7	Gloss
	Sp-2-m	Sp-2-g	28.0	8.23	31.4	24.3	17.5	21.9	Gloss
	Sp-4-m	Sp-2-m	23.0	13.7	43.6	12.2	18.3	22.2	Size
	Sp-4-g	Sp-2-g	11.4	24.4	25.3	24.1	6.4	18.3	Size
(b)	Sp-4-m	Co-4-m	11.3	29.8	18.9	19.9	22.0	20.4	Shape
	Sp-4-m	Cy-4-m	18.9	25.3	16.2	18.7	7.17	17.3	Shape
	Co-4-m	Cy-4-m	10.9	5.8	3.1	5.3	29.3	10.9	Shape
(c)	Sp-4-g	Co-4-g	10.3	33.7	18.4	12.9	7.3	16.5	Shape
	Sp-4-g	Cy-4-g	53.6	14.7	24.8	27.3	9.4	*25.9*	Shape
	Co-4-g	Cy-4-g	47.4	29.6	11.1	16.4	13.9	23.7	Shape
Average			23.5	21.0	21.9	16.5	13.5	19.3	

The last column in Table 5 shows the variables of the two data sets. The *STRESS* value of the difference between the chromaticity ellipses of each data set in the CIELAB space is used to quantify the effect of different variables. The largest difference is 25.9 between the spherical glossy samples (Sp-4-g) and the cylindrical glossy samples (Cy-4-g), only with shape difference in the two groups. Meanwhile, the smallest difference is 10.9 for Co-4-m and Cy-4-m, with shape difference in the conical matte samples and the cylindrical matte samples. The results indicate that glossy shapes will greatly affect the visual results, see the results from Fig. 12(e).

3.4.2 Comparing with JIANG LAN's study

The current experimental results for each colour center were compared with those found in previous experiments from Jiang Lan et al.[16]. The main information about Jiang Lan's experiment is summarized in Table 6.

Table 6. Main information of Jiang Lan' s experiment

Data set	Light sources	Samples(pairs)	ΔE^*_{ab} range	$\overline{\Delta E^*_{ab}}$	Method
DS	Diffuse light	Sphere(75)	2.9~23.6	10.3	Grey-scale
DF	Diffuse light	Flat(75)	0.3~24.3	6.7	Grey-scale

The light source and visual experiment method in our experiment Sp-4-m are similar to the DS and DF data sets obtained in their work. The difference between the two studies is that in Sp-4-m, the colour difference belongs to the small and medium colour difference magnitudes, with the mean value of 5.0. While in Jiang Lan's DS sample pairs, the colour difference is larger than present study, with the mean value of 10.3. The Monte Carlo method proposed by Strocka et al.[35] was also used to analyze the relationships between the ellipses from Sp-4-m and DS, DF in Jiang Lan's study. The *STRESS* values found from ellipse's equations are shown in Table 7. The best for each phase is indicated in bold and the worst is underlined.

Table 7. *STRESS* values between the results from the present study and those from Jiang Lan' s.

1st Data (Present)	2st Data (Jiang Lan's)	Grey	Red	Yellow	Green	Blue	Average	Variable
Sp-4-m	DS	20.0	**6.3**	22.1	15.1	<u>35.1</u>	19.8	Colour difference
Sp-4-m	DF	24.3	**22.6**	<u>38.9</u>	26.0	33.7	29.1	Shape

In the comparison of the chromaticity ellipse differences between the Sp-4-m and the DS, DF data sets from Jiang Lan's study, the shape had a greater influence than colour difference magnitudes on the visual colour difference computed by different chromaticity ellipses. It can also be seen that the difference between the plane and the sphere on the chromaticity ellipse is larger than the difference between other shapes in Table 5, which had the maximum *STRESS* value of 25.9 amongst different shapes.

4. Discussion and Conclusion

In this study, 440 pairs of 3D samples with different shapes (spheres, cones and cylinders), different sizes (4 cm and 2 cm), and different optical properties (matte and glossy) were prepared by Sailner 3D colour printers, surrounding the CIE five colour centers (grey, red, yellow, green, and blue). These samples were divided into four experiments with a total of eight phases. The average CIELAB colour difference of each phase sample is 4.74-6.16, belonging to the magnitudes of small and medium colour difference. 26-45 observers performed the visual experiments with the grey scale method and finally 191 sets of visual datasets were collected.

The parametric effects (gloss, 3D shape and size) on the perceived colour difference were compared by the visual colour differences and chromaticity ellipses. The results showed:

a) The visual colour difference of the matte sample pairs increased by 10.9% compared to the glossy sample pairs. As the $\Delta V/\Delta E^*_{ab}$ values of the matte samples were larger than those of the

glossy samples, and the sizes of the matte and gloss samples had little differences, it can be concluded that the major visual differences between the matte and glossy samples were lightness differences since the mean differences of the chromaticity ellipse size are very small. b) Comparing different 3D shapes, it was found that the spheres possessed larger visual colour differences compared with those with the shapes of cone and cylinder when they have similar $\Delta E^*_{ab,10}$. In the matte and glossy sample sets, the visual colour differences for spheres increased 2.7% and 13.6% with respect to the values found for the cones, and it increased 5.5% and 6.9% with respect to values found for the cylinders, respectively.
c) The visual colour differences of 4 cm spheres are greater than those of 2 cm spheres. In the matte and glossy sample sets the visual colour differences for spheres of 4 cm increased 9.3% and 31.8% with respect to values found for spheres of 2 cm, respectively.

The chromaticity ellipses were calculated to compare the colour difference and the consistency of different parameters with the indices of the size of the ellipses and the *STRESS* value respectively, the results indicated that the glossy samples with different shapes will arouse quite different visual perceptions, especially for sphere and cylinder samples. Beside the high number of visual assessments performed in the current work, following CIE recommendations on color difference evaluation[36] we feel that new reliable experimental data are necessary, in particular for 3D objects.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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