Development of a perceptually uniform physical scale for visual assessment of specular gloss

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Abstract

Measuring gloss, visually or instrumentally, has been a challenge in many manufacturing and service industries. However, there exists no standardized method for visual evaluation of equidistance specular gloss. This study aimed to design and prepare a psychometric visually equispaced specular gloss scale for the visual measurement of gloss or any other geometric appearance attribute. To this end, a series of lithographically printed black papers, with different levels of gloss from low to high, were prepared to constitute a visually uniform specular gloss scale. Fourteen observers visually quantified the scale in a unidirectional illumination at three different geometries. Analyzing the results shows that the 60° geometry can quantify the equivalent specular gloss efficiently. A uniform specular gloss scale was prepared by assessing the prepared scale visually under the unidirectional illumination at the 60° geometry. Such a visually uniform specular gloss scale could be employed to develop a standard visual evaluation method of specular gloss in all related industries.

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1. Introduction

As one of the most significant geometric characteristics of visual appearance, gloss plays a substantial role in many industries, such as automotive, surface coatings, and printing [1]. Among various gloss attributes, first recognized and defined by Hunter [2], the specular gloss has been the most popular for many years. Such geometric appearance attributes resulting in a shiny bright surface arise from the selective reflection of white light by the object at a certain angle of observation [3]. In other words, gloss perception is related to the reflection of white light by an object that is observed from different angles, mainly reflected light at or near the specular angle [4].

Ingersoll made one of the earliest attempts to establish an objective method for specular gloss measurement in 1914 [5], which was based on the fact that the specularly reflected light is almost wholly polarized, as opposed to the diffusely reflected light. The Ingersoll's 'glarimeter' adopted the 57.5° geometry for measuring the specular gloss with the aid of a polarizing filter.

In the early 1930s, Hunter [2] was the first to design a photoelectric glossmeter capable of measuring the specular gloss at the 45° geometry. Only an established method for measuring the specular gloss as a single physical index had been sought after that time. However, the demand for a reliable objective measure of specular gloss was eventually transferred into the study's perceptual domain [6].

After Hunter's proposed method, visual evaluations of various surfaces' specular gloss in comparison with instrumental measurements demonstrated that the 60° geometry is more appropriate for measuring perceived gloss [2]. Many efforts were subsequently undertaken to establish a standard procedure for instrumental measurement of specular gloss.

According to the ASTM standard D523 [7], specular gloss is a measure of specular luminous reflectance of a specimen under geometrical and spectral conditions. The specular gloss of the standard is considered to be

Table 1. Visual (ΔE_v) and Instrumental (G_i) data for the black specular gloss scale samples.

Sample	$G_{i,20}$	$G_{i,60}$	$G_{i,85}$	$\Delta E_{v,20}$	$\Delta E_{v,60}$	$\Delta E_{v,85}$
S1	85.5	96.6	108.8	0	0	0
S2	53.6	85.4	102	5.9	4.1	2.6
S3	35.2	75.2	100.4	8.2	6.1	4.2
S4	24.5	69.6	96.1	9.8	8.2	4.8
S5	14.9	54.4	96.5	12.3	7.4	6.1
S6	10.4	46.5	93.7	13.3	9.9	6.7
S7	7.3	37.6	93.5	15.7	10.4	7.7
S8	4	28.1	91.1	18.8	13.1	8
S9	2.5	23.9	89.3	24.8	16.7	9.9
S10	2.4	8.4	83.6	26.4	20.4	12.9
S11	0.2	2.5	60.2	32.4	29.6	22.3

100% at all illumination/detection angles. First, the gloss of the sample is measured at the 60° geometry. If the result is more than 70, it is measured again at the 20° geometry, and if it is less than 10, the measurement should be made at the 85° geometry.

Despite the lack of proper relationship between measured and visually perceived gloss demonstrated in several research works [8–23], glossmeters are extensively utilized to evaluate gloss in industries.

The conventional glossmeters can quantify the specular gloss of surfaces in accordance with a standard procedure. The readings of such measuring instruments are rather comparative readings. They do not indicate to what extent such readings are visually significant to promote settings of gloss tolerance limits.

In this regard, having a psychometric specular gloss scale in which the scale samples are visually equispaced is another critical and sought after issue to be dealt with. Such an equispaced specular gloss scale could be a beneficial device for precise visual evaluation of gloss differences in achromatic and chromatic specimens. Using such a uniform scale would facilitate the development of a standard procedure for visual assessment of specular gloss. Additionally, such a tool would be very helpful in setting acceptable tolerance limits in various industries.

A recent study [24] has shown that the instrumental 60° geometry can quantify the specular gloss perceived by a human observer. In the present research, however, efforts were made to design and make up an achromatic psychometric visually equispaced specular gloss scale in which the specular gloss differences of the scale samples are visually equal. A set of black samples with low to high gloss values were prepared and subsequently quantified visually by observers, in a unidirectional lighting cubicle, at 60°/60° geometry. A commercially available instrument also measured the gloss of samples. Such instrumental measurements together with the corresponding human-based evaluations of specular gloss, were employed to design a psychometric visually equispaced specular gloss scale.

2. Materials and methods

A white semi-glossy paper with a gloss value of 30 G.U. at 60° was employed for preparing the samples. An offset-lithographic printing technique was used to prepare a black achromatic sample with CIE L^*, a^*, and b^* values of 33.12, 1.61, and 2.73, respectively CIE illuminant D65 and 1964 standard colorimetric observer.

A glossy clear coat provided by the Farabanafsh Co. (Iran) was used. Different amounts of a matting agent (silica-based) were incorporated to obtain various levels of gloss from fully-glossy to matte. A 12 μm thick overprint layer containing a certain amount of matting agent was applied on each 20×10 cm^2 black paper sample. The clear coats were cured in 365 nm wavelength U.V. with a power flux of 24 W/cm^2. Thus, 11 samples from low to high gloss were produced, constituting a gloss scale.

The BYK-Gardner micro-Tri-gloss glossmeter was used for measuring the gloss of the samples, and all the samples were measured in three geometries, i.e., 20°, 60°, and 85°.

The measured values of the 11 samples of the specular gloss scale, coded as S1 to S11, are given in table 1. The measurement results are presented as $Gi_{,20}$, $Gi_{,60}$, and $Gi_{,85}$ for the 20°, 60°, and 85° geometries, respectively.

A designed uniform lightness scale was utilized to quantify the samples' specular gloss visually [25–27]. This scale was composed of eight $10\ ^*\ 20$ cm^2 gray matte polyester fabrics having the same chromaticity and varying only in lightness values [28]. The visual evaluations were carried out under the following conditions in a dark cubicle: unidirectional illumination with the level of 7000 lux luminance and a CCT (correlated color temperature) 5600 K. For visual assessment at 20°/60°/85° illumination/observation geometries, an inclined table was used at a distance of 50 cm from observer's eye.

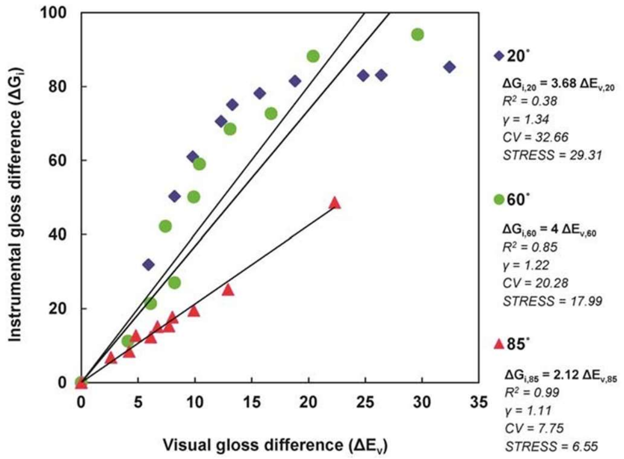

Figure 1. Correlation between visual and instrumental differences for three different geometries.

Visual evaluations were performed by 14 observers with regular color visions who passed the Ishihara test. Our observers were comprised of nine females and five males who were research students and staff; their ages ranging from 23 to 49 years. Statistical analysis of our study shows that the STRESS for inter-observer disagreements was less than 25 percent which is comparable to the STRESS of the inter-observer disagreements. Such STRESS values attained are far below the STRESS values reported by other authors using a maximum of 10 observers [29, 30].

The observers reported the differences in the gloss of each sample (S2 to S11) with the standard, namely the sample with the highest visual and instrumental specular gloss value (S1), according to the lightness difference in the lightness scale (i.e., ΔE_v) [25, 26]. Such visually perceived specular gloss differences for three geometries: 20°, 60°, and 85° are shown in table 1.

For evaluating the correlation between instrumental and the corresponding visual data, the four statistical parameters, namely coefficient of determination (R^2), Gamma (γ), coefficient of variation (CV), and standard residual sum of squares (STRESS), were utilized [31, 32].

3. Results and discussion

Having obtained visually perceived specular gloss differences according to the lightness difference of the lightness scale (i.e. ΔE_v), the first step was to determine the errors involved in visual assessments. The STRESS parameter was used for determining the inter-observer variability for observers. There is a good agreement between the observers as the STRESS value is 23%. The average value of ΔE_vs given for all observers are reported in table 1. Since the observers were requested to inform the differences in specular gloss, the equivalent instrumental differences (ΔG_i) were also calculated, separately for the 20°, 60°, and 85° geometries, as the difference between the instrumentally measured specular gloss of each sample (i.e., $G_{i,20}$, $G_{i,60}$ and $G_{i,85}$) and the standard.

To determine which of the three measuring geometries is the best quantitative representation of the visually perceived specular gloss, the relationship between visual results and instrumental measurements was studied. Figure 1 shows the correlation and statistical parameters, namely R^2, γ, STRESS, and CV values.

Figure 1 indicates that high and semi-gloss samples (having specular gloss values higher than 20 G.U.) give linear correlations for the 20° geometry. The 85° geometry only for the semi-glossy and matte subdivisions gives a nearly perfect linear correlation. However, while the observers are conveniently able to perceive and quantify the differences in the samples' specular gloss at the geometry of 85°/85°, the respective instrumental differences are not meaningful in the same way. In other words, small instrumental gloss differences have been obtained at the geometry of 85° while the corresponding visual differences are much larger in magnitude. On the contrary, there is a high correlation between visual and instrumental equivalents data over the entire range of specular gloss in the 60° geometry.

Having obtained a strong relationship between the visually quantified and the corresponding instrumentally evaluated equivalents at the 60° illumination/observation geometry, this geometry was employed to design a psychometric visually equispaced specular gloss scale.

A brief look at the scatter plot in figure 1, however, indicates that the specular gloss scale does not seem to be uniform in terms of the 60° visual gloss, as the visually perceived specular gloss differences ($\Delta E_{v,60}$) of each of the

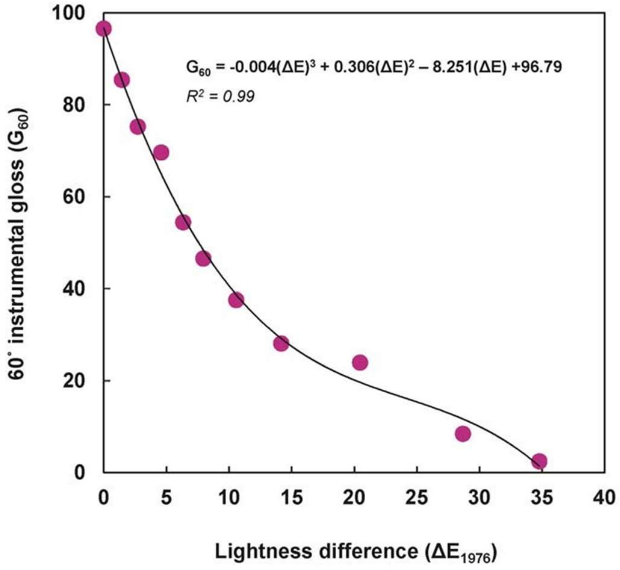

Figure 2. Correlation between the samples' instrumental gloss values at the 60° geometry ($G_{i,60}$) and the lightness differences (ΔE_{1976}).

Table 2. Visual and instrumental differences of specular gloss for consecutive adjacent samples of the specular gloss scale.

Adjacent sample pair	$\Delta G_{i,60}$	$\Delta E_{v,60}$
S1–S2	11.2	5.3
S2–S3	10.2	5
S3–S4	5.6	3.8
S4–S5	15.2	6.2
S5–S6	7.9	3.5
S6–S7	8.9	3.3
S7–S8	9.5	3.4
S8–S9	4.2	2.5
S9–S10	15.5	6.1
S10–S11	5.9	4.4

two consecutive adjacent samples are not identical. To put this to test, the same panel of observers visually quantified the differences in the two adjacent samples' specular gloss under the unidirectional illumination at the 60° illumination/observation geometry. The results of such visual assessments, as well as the corresponding instrumental differences, are presented in table 2.

From table 2 and figure 1, it can be inferred that such a specular gloss scale is not visually uniform. The visually perceived specular gloss differences of the first two samples, namely S1 and S2, and the samples S4 and S5, and S9 and S10 are much larger than the rest of the differences.

To design the visually equispaced specular gloss scale, we employed our visually uniform designed lightness scale, by which the observers quantified all visual differences in specular gloss.

As a standard measure, the 'Gray scale' [33], which is essentially a lightness scale, has been utilized to quantify the differences in various color attributes and the total color difference. The samples' lightness differences with the standard increase according to a geometric progression in such a lightness scale. Assuming that the human visual system perceives specular gloss in the same way as lightness is perceived, the correlation between lightness differences of the designed lightness scale, in terms of the ΔE_{1976}, and the 60° gloss values ($G_{i,60}$) was investigated. Figure 2 illustrates such a correlation.

Figure 2 indicates that a cubic polynomial, giving $R^2 = 0.99$, represents the data's best-fitted model. Equation (1) shows such a correlation:

$$G_{i,60} = -0.004(\Delta E_{1976})^3 + 0.306(\Delta E_{1976})^2 - 8.251(\Delta E_{1976}) + 96.791 \quad (1)$$

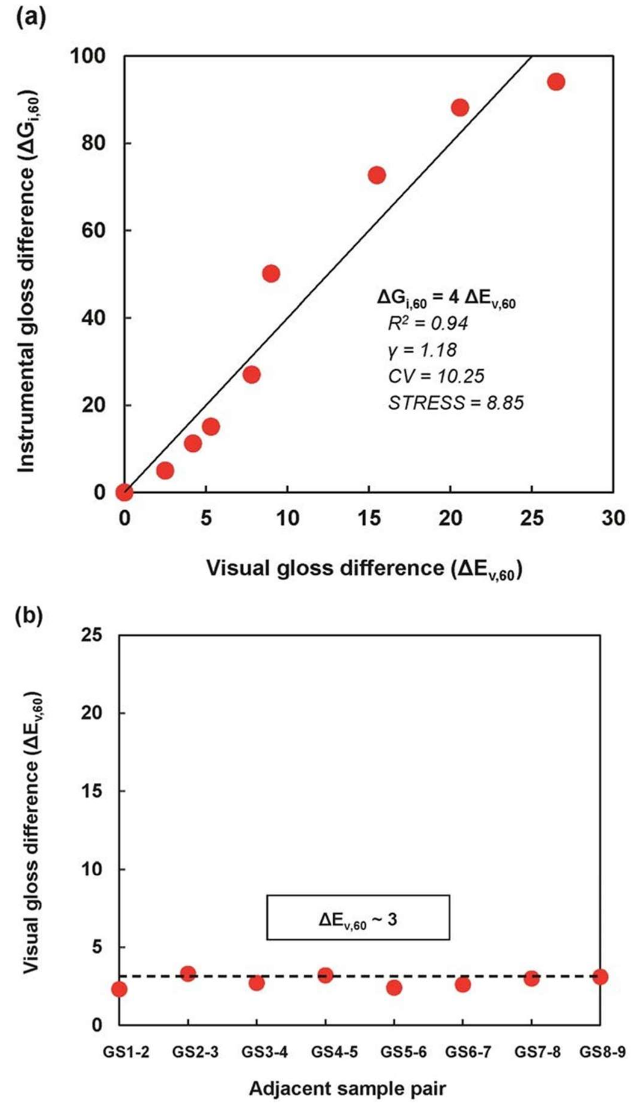

Figure 3. Correlation between visual and instrumental data for gloss scale.

Table 3. Instrumental and visual data for the newly prepared gloss scale.

Sample	$G_{i,60}$	$\Delta G_{i,60}$	$\Delta E_{v,60}$	Adjacent sample pair	$\Delta G_{i,60}$	$\Delta E_{v,60}$
GS1	96.6	0	0	GS1−GS2	5	2.3
GS2	91.6	5	2.5	GS2−GS3	6.2	3.3
GS3	85.4	11.2	4.2	GS3−GS4	3.9	2.7
GS4	81.5	15.1	5.3	GS4−GS5	11.9	3.2
GS5	69.6	27	7.8	GS5−GS6	23.1	2.4
GS6	46.5	50.1	9	GS6−GS7	22.6	2.6
GS7	23.9	72.7	15.5	GS7−GS8	15.5	3
GS8	8.4	88.2	20.6	GS8−GS9	5.9	3.1
GS9	2.5	94.1	26.5			

For given lightness differences (ΔE_{1976}) of 0, 0.5, 1, 2, 4, 8, 16 and 32, the respective 60° specular gloss values ($G_{i,60}$) were interpolated using equation (1). Such lightness differences vary according to a geometric progression and represent equal differences in visually perceived lightness. The corresponding 60° specular gloss values ($G_{i,60}$) are 96.8, 92.7, 88.8, 81.5, 68.4, 48.2, 25.8 and 8.1, respectively.

To design a uniform specular gloss scale, the samples having the closest 60° specular gloss values to such interpolated specular gloss values were selected from the 11 samples of the specular gloss scale. For those

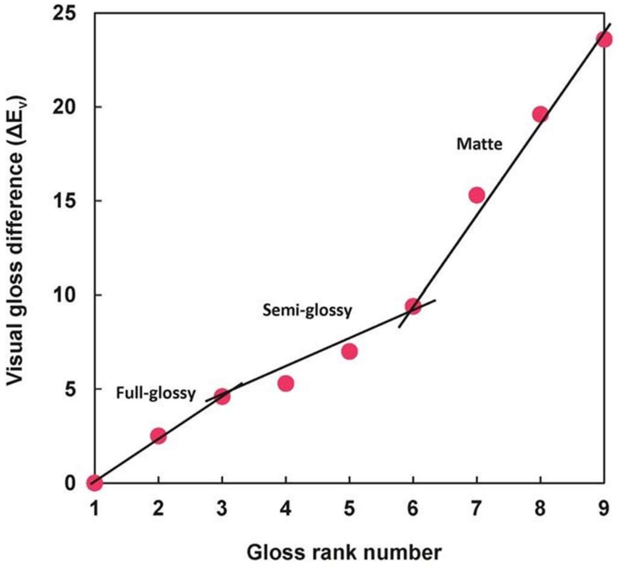

Figure 4. Correlation between gloss rank numbers versus the corresponding visual gloss differences ($\Delta E_{v,60}$).

in-between specular gloss values in which there was no equivalent in the gloss scale, new samples were prepared and included in the original sample set.

In that manner, a gloss scale including nine samples, from low to high gloss, was prepared as an initial foundation for a gloss scale with uniform visually equispaced.

For finding out if the newly prepared gloss scale is visually uniform, the same panel of observers performed their visual assessments. Besides evaluating the specular gloss differences between each sample and the standard (with the highest visual and instrumental specular gloss value), the specular gloss difference between each two consecutive adjacent samples was also evaluated at the 60° illumination/observation geometry. The results of such visual assessments and the corresponding instrumental measurements are depicted in table 3. The nine samples of the new scale in table 3 are coded as GS1 to GS9. For each sample and sample pair, all observers' average visual differences (ΔEv) are reported.

The correlation between visual differences ($\Delta E_{v,60}$) against the corresponding instrumental gloss differences ($\Delta G_{i,60}$) for the newly prepared specular gloss scale is depicted in figure 3(a). Additionally, the variation of visually perceived differences in specular gloss ($\Delta E_{v,60}$) for each of the two adjacent samples is also illustrated in figure 3(b).

Again, there is a high linear correlation between instrumental gloss differences ($\Delta G_{i,60}$) and visual differences ($\Delta E_{v,60}$) at the 60° illumination/observation geometry (see figure 3(a)). Moreover, figure 3(b) shows that the visually perceived gloss differences between each of the two adjacent samples seem to be satisfyingly equal, indicating that such a specular gloss scale is now visually uniform.

However, some interesting facts regarding the visual perception of specular gloss can be drawn here. Suppose the entire gloss area is divided into the following three parts at 60°: (80−100 GU) high-glossy, (20−80 G.U.) semi-glossy, and (0−20) matte. In that case, it is clear that the instrumentally measured specular gloss differences for fully-glossy and matte subdivisions are smaller than those for the semi-glossy subdivision. However, the respective visual differences are relatively equal. Figure 4 illustrates such a human visual sensitivity to the presently proposed uniform specular gloss scale's specular gloss variations.

It can be inferred from figure 4 that in comparison to semi-gloss samples, the sensitivity of variation of gloss in high-gloss and matte samples are much more among the observers (i.e., the steeper slope of the fitted line). The present authors have already demonstrated such results in a previous study [24].

High-gloss samples' higher sensitivity can be attributed to the fact that surfaces with high gloss are mainly evaluated visually by focusing on the distinctness of the reflected image on the surface, which is easily perceived by the observers. On the other hand, for low gloss surfaces, the specular reflection is negligible, and the diffuse reflection dominates. For such surfaces, specular gloss is visually evaluated by focusing on lightness variations, proven to be the most understandable perceptible difference for the human perception system [34, 35]. The perceived lightness increases by increasing the specular gloss of the matte surfaces.

It is well known that various industrial products' appearance-related parameters have been traditionally judged by an expert, believing that human judgment is the final determinant. Different standardized methodologies have been developed over the years to evaluate color appearance attributes in this relation visually. AATCC recommends some test methods for visual assessment of color change and staining of textiles using the 'Gray scale' during color fastness tests [36, 37].

Additionally, the ASTM describes a test method that utilizes the 'Gray Scale' to assess the change in color [33].

There are also standard methods, recommended by the ASTM and the ISO, for visual assessment of color changes of liquids using the Platinum-Cobalt scale [38, 39], and also for transparent liquids such as oils and varnishes by the aid of the 'Gardner scale' [40, 41].

However, despite the importance of geometric appearance in many industries, no standard method has been developed to visually evaluate geometric attributes of appearance, such as specular gloss, with the aid of a physical scale.

The presently proposed visually equispaced specular gloss scale can be efficiently employed to assess specular gloss or any other geometric appearance attribute visually. Such a uniform scale and a unidirectional illumination compartment proposed and utilized in this work make provisions for developing standard methods for visually evaluating gloss of various surfaces from fully-glossy to matte.

4. Conclusions

A set of black paper samples with different gloss values from high-glossy to matte were made to constitute a visually equispaced specular gloss scale. The prepared gloss scale was visually assessed by observers under a unidirectional illumination at three geometries, namely 20°, 60°, and 85°, using an also prepared lightness scale. Also, samples were instrumentally measured in accordance with the ASTM standard at the three measurement geometries by a conventional glossmeter.

Visual and instrumental measurements of differences in gloss values were linearly correlated at the 60° illumination/observation geometry. The results also show that the measuring geometry of 60° is much more efficient than other measuring geometries for evaluating gloss in the range of matt to high-glossy and is similar to human performance in assessing gloss attribute. A visually uniform specular gloss scale in which the samples have equal visual differences in gloss was successfully designed and prepared. Such a visually equispaced specular gloss scale shows that observers are much more sensitive to the variation of specular gloss of matte and high gloss samples than semi-gloss samples. Developing standard methods for visual evaluation of gloss of various surfaces from fully glossy to matte would be facilitated by the presently proposed uniform specular gloss scale.

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