Statistical design of experiments applied on sparkle visual detection

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Abstract

In this work, we have focused on analyzing how different variables affect in the process of detecting the sparkle texture effect, since there are few works related to this issue. A large number of samples were available with different characteristics depending on the needs of each psychophysical experiment. The studied parameters were structural variables such as pigment type, size and concentration, and environmental variables such as illumination and viewing conditions.

Due to the large sample number, the design of experiments (DoE) was applied to optimize the psychophysical experiments and to evaluate which variables affect individually on the sparkle detection, as well as if there are interactions among them. After collecting all the information from the psychophysical experiments, with more than 35.000 visual assessments performed, the correlation with the instrumental data of the BYK-mac was verified to corroborate its reliability.

It has been possible to demonstrate the influence of multiscale parameters on the sparkle appearance and to extract which variables affect to a greater extent when detecting the sparkle texture effect. This issue was fundamental because, there was no previous study addressing these issues, which was of vital importance for the industry to analyze how the sample texture is detected depending on various conditions, whether structural, environmental, etc.

In addition, a reliable and applicable methodology has been implemented for other types of existing goniochromatic pigments with novel texture effects. It has been possible to implement the design of experiments as a main tool to limit the visual experiments to be performed, making the fewest visual evaluations possible and obtaining the maximum results.

Thanks to psychophysical experiments, it has been successfully tested the visual and instrumental correlation of sparkle detection between the only multi-angle device on the market to date, and the visual assessments obtained from a large number of observers.

Introduction

Interest in goniochromatic pigments (metallic, pearlescent or interference, and diffractive) has not stopped of growing for several years, on diverse industries as plastics, cosmetics, ceramics, printing inks, paper and board, paints and coatings, etc. These effect pigments offer attractive visual characteristics to satisfy the market needs. Therefore, there is a growing trend to use more metallic and pearlescent finishes instead of traditional solid or homogeneous colors.

In particular, the special-effect pigments have gonio-appearance behavior. That is, their color appearance is characterized by lightness, hue and chroma variations according to the measurement geometry. In addition, special-effect pigments also show texture effects known as sparkle and graininess. Therefore, the visual perception of these materials will not only depend on color, but it will also be influenced by the textured effect that the metallic particles or other pigments cause in the sample. Like color, these textured effects also change with illumination conditions, as for example, when observing the same sample with direct or diffuse illumination it is perceived differences in the visual appearance. Furthermore, they will also depend on other parameters such as the viewing distance, illumination and observation angles, background color, etc.

Sparkle is an optical effect characterized by micro gloss, blink (flash) or a diamond effect when the sample is illuminated with a direct light, such as sun directly illumination. The sparkle grade (greater or lesser intensity) depends on the reflectivity in the individual effect pigment (flakes made of aluminum, mica, etc.), the concentration, size and orientation of the particular special-effect pigment [1] Nowadays, there is only one instrument on the market to measure these texture effects: the BYK-mac multi-angle spectrophotometer [2]. This instrument has 6 measurement geometries for color characterization and it also has a monochrome CCD camera for the texture measurements. Images from the camera are taken under different illumination conditions in order to simulate direct illumination for the sparkle measurement. In particular, the sparkle is encoded under three illumination angles: 15ºas15º, 45ºas45º and 75ºas75º.

Nevertheless, there is no international standard like ISO, ASTM or DIN, that defines the mathematical and optical algorithms to measure and calculate the sparkle degree. Thus, there are many related open questions about this texture effect: visual detection distance, measurement geometries, the illumination level influence, effect of the spectral distribution of the light source used, discrimination vs. detection tasks, colorimetry influence (lightness, hue or chroma of the sample), etc. However, these new texture effects are important for the visual discrimination of many materials and to apply the quality control. Therefore, the objective of this work is to develop and consolidate a reliable and useful methodology for visual evaluation of the sparkle texture effect in order to determine the most important variables with influence on the sparkle detection.

Materials and Methods

Due to the multitude of variables that affect the sparkle texture effect detection [3], such as the pigment type, size, shape, concentration, orientation, the colorimetry of the sample, etc., diverse psychophysical experiments are conducted by the design of experiments [4], to optimize the variables involved in each experiment. With these experiments we intend to study the following aspects:

- Check the instrumental correlation of the sparkle by the magnitude estimation method (Exp 1) [5].
- Determine the sparkle visual detection distance and establish a relationship with the particle size of the effect pigments and/or their shape (Exp 2) [6].

- Determine the influence of the light source spectrum and its colorimetric performance, as well as the illumination level on the sparkle perception. It is well known that the spectral distribution of the light source plays a very important role in the perception of color, however, nothing is known about its influence on sparkle perception (Exp 3).
- Determine the influence of effect pigment density/concentration on sparkle detection (Exp 4).
- Evaluate and corroborate if the algorithm [1] proposed by CSIC Optics Institute (IO-CSIC) is correlated with the instrumental measurements provided by the BYK-mac, and with the visual measurements provided by the observers in the psychophysical experiments carried out (Exp 5).

The experiment 1 was based on the magnitude estimation method. The visual experiment was conducted on the byko-spectra lighting cabinet. In particular, two measuring geometries were used, 15ºas15º, 45ºas45º, following the ASTM standards nomenclature, or 15ºx:0º and 45ºx:0º, following the CIE nomenclature and two illuminance levels, 800 and 2400 lux. The viewing distance to the samples was 60 cm. To fix the size of the stimuli, a mask was used with a size of 7 x 7 cm. The number of samples used for this experiment was 91 and the number of participants was 11 with normal vision (normal color & visual acuity equal to 1 with the best correction). In this experiment the question to the observer was to quantify the sparkle magnitude by considering two anchors (with values of 0 and 10, respectively) by assigning intermediate numbers in proportion to the magnitude of the stimulus (anchors). These anchors were determined taking into account the sparkle value provided by the BYK-mac multi-angle spectrophotometer with a minimum and maximum sparkle grade. Three repetitions were done in a 30 minute session, therefore a total of 12.012 visual evaluations were done.

For the experiments 2-4, a large number of samples were collected from different suppliers (Eckart, Schlenk, BASF Coatings, Merck), with different pigment types (Luxan, AluMotion, Variochrom, Stapa, Iriodin, Xirallic, etc.) and with varied pigment sizes ranging from 5 µm to 90 µm, covering the maximum possible size ranges. Therefore, the statistical design of experiments (DoE) was considered to optimize the experimental work [4], that is, to know the minimum number of samples involved in the visual experiments to obtain the maximum information. In most of the designs of experiments proposed throughout the work, we selected a factorial design 2^2, since there were two factors or variables (for instance, size, shape or illuminance level) at two different levels (small, high; silverdollar, cornflake, 800 lx, 2400lx, respectively). In some cases, a 2^3 factorial design was chosen due to that more variable were considered. With this design, the effects of individual factors were studied, and depending on the chosen design, the effect interaction (non-linear or linear) of the different levels between different factors was also evaluated.

Therefore, the main objective of these visual experiments was to study the influence of different factors, either quantitative (size, concentration, etc.) as qualitative (shape, etc.) on the response average, in our case the detection of the sparkle texture effect. For these visual experiments, a new lighting booth was used. It was specially designed to detect, scale and even discriminate sparkle at different distances, with different lighting geometries and with different light sources. The cabin has an adjustable arm to select the illumination geometry, to change the light source and to modify the intensity as required at each time. The method used for these visual assessments was the method of adjustment, which is one of the oldest and most fundamental of Psychophysics: the subject must adjust or manipulate the stimulus intensity (sparkle), until it is able to perceive it, or to stop perceiving it, in this case, by adjusting the distance at which the sparkle is detected in the sample. In this way, the observer was in front of the samples from a close distance (10 cm) and he was increasing the distance until not to detect sparkle (3 repetitions). Moreover, for other three repetitions, the observer was in front of the samples from a long distance (400 cm) and he was reducing the distance until to detect sparkle. The height of the eyes was adjusted to the same height as the light source and sample, and before starting they spent some minutes for adapting the lighting conditions of this visual experiment. The number of observers who participated in the experiment was 12 with normal vision.

In total, after four psychophysical experiments, more than 35.000 visual evaluations were made. Subsequently and for each of the experiments, it was studied that the assessments of all the observers were consistent by studying the intra-variability and inter-variability with the STRESS parameter [7].

On the other hand, two different instruments were considered to evaluate the visual and instrumental correlation. On one hand, the BYK-mac multi-angle spectrophotometer was used to obtain the sparkle values at different measurement configurations. On the other hand, all the same samples were measured with the Spanish gonio-spectrophotometer (GEFE) [8-9] under the same measurement configurations.

Results

Experiment 1: Sparkle Magnitude Estimation

The objective of this experiment was to study the visual and instrumental correlation of sparkle between the only commercial device available on the market capable of measuring this texture effect (BYK-mac) and what the human eye detects. It was studied in two measurement geometries (15ºas15º and 45ºas45º) and for two illumination levels (800 and 2400 lx).

To evaluate the results, it was studied the relationship between instrumental and visual sparkle estimations. A good correlation was found since it was found a linear relationship with a correlation coefficient around 0.85. In particular, it is important to mention that for the low illuminance level (800 lx), no differences were found regarding the measurement geometry. However, for the high illuminance level (2400 lux), sparkle was slightly better scaled in the 45ºas45º geometry (Figure 2) with a correlation coefficient close to 0.87.

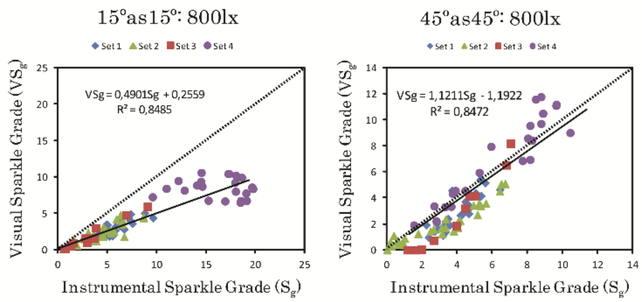

Figure 1. Sparkle grade correlation for the low illuminance conditions (800 lux) for the 15ºas15º (left) and 45ºas45º (right) measurement geometries.

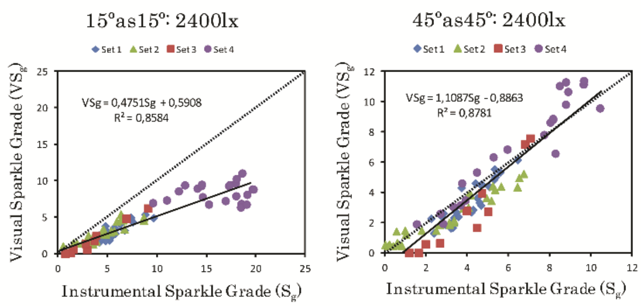

Figure 2. Sparkle grade correlation for the light illumination conditions (2400 lux) for the 15ºas15º and 45ºas45º measurement geometries.

Experiment 2: Influence of the effect pigment size and shape on the sparkle detection distance

This experiment was focused on determining the influence of the pigment size and shape. Following the design of experiments, two different pigment shapes were considered: silverdollar and cornflake, with two different pigment sizes: small (9 µm) and large (35 µm). After analyzing the results from the visual experiment, the results show that has more relevance the pigment size than the pigment shape because for very small particles sizes the sparkle is not detected. Therefore we do not care the pigment shape because the sparkle texture effect will not be detected. In addition, thanks to the design of experiments it has been possible to analyze the influence of these two variables and the interaction between them (Figure 3). Finally, a model to determine or calculate the maximum sparkle detection distance regarding the pigment size was established. In particular, the best regression model for these data was a second order polynomial also including the qualitative variable of pigment type (Figure 4).

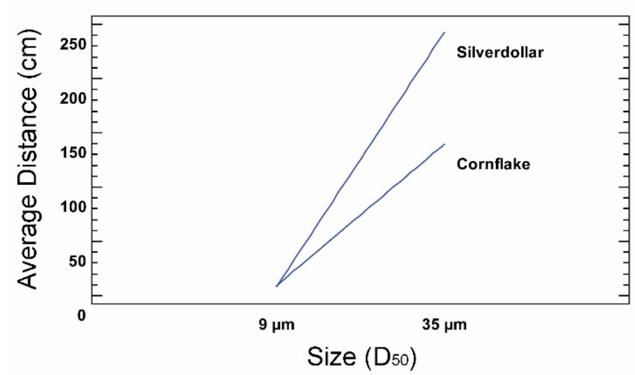

Figure 3. Interaction between shape and size for metallic effect pigments.

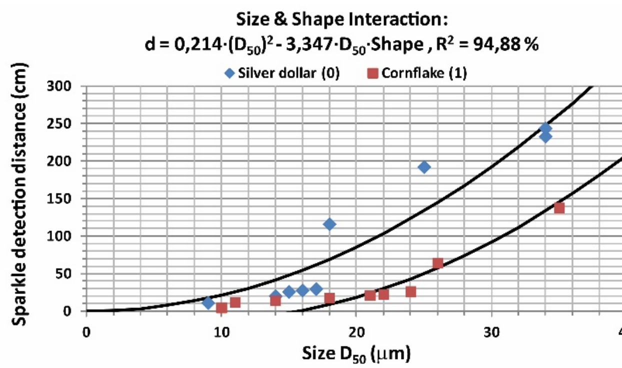

Figure 4. Regression model for pigment shape and size interaction.

Experiment 3: Influence of the environmental variables on the sparkle detection

In this experiment, the objective was to analyze the influence of the environmental variables in the sparkle detection, in this case, the influence of the light source, the illumination level and the measurement geometry. For this, two kinds of light sources were used, warm light (CCT = 3200 K) and cold light (CCT = 6500 K), with two illumination levels (800 and 2400 lx) and three measurement geometries (15ºas15º, 45ºas45º and 75ºas75º). The results obtained were that for low illumination levels (800 lx) the sparkle can be detected at a greater distance (Figure 6), this may be because under specific illumination conditions, the human eye is not able to clearly distinguish the small reflections produced by the flakes. For the same illumination level, the geometry to which the texture effect is best detected is for the 45ºas45º geometry (Figure 5).

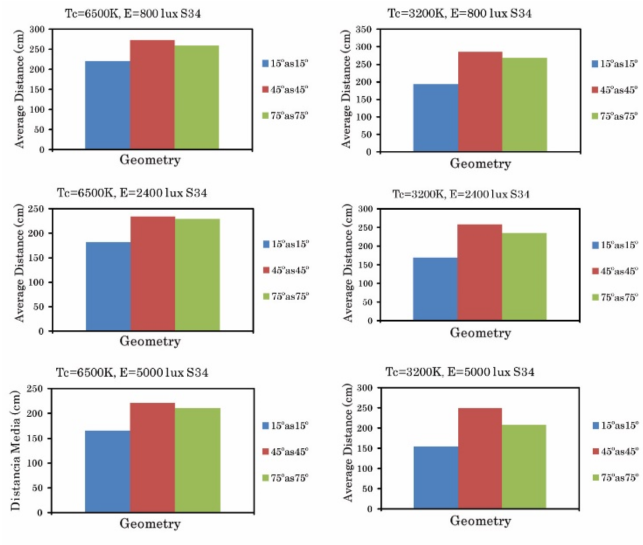

Figure 5. Measurement geometry influence on the sparkle detection distance for samples with metallic pigments.

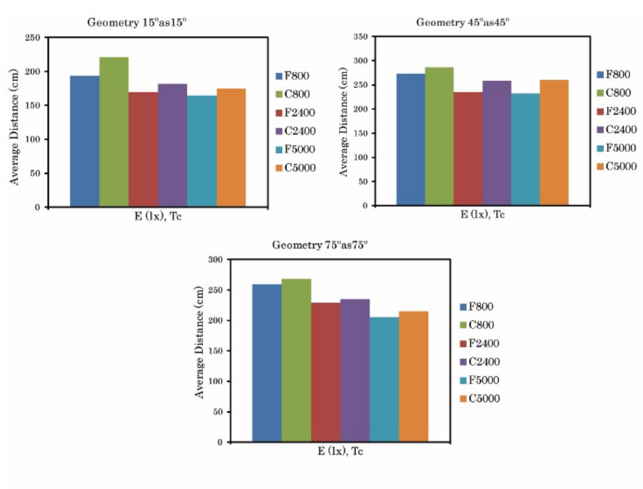

Figure 6. Color temperature and illumination level influence on the sparkle detection distance for metallic pigments.

Experiment 4: Influence of the pigment concentration/density and the sample lightness at the sparkle detection distance

For this experiment the pigment size was fixed and only the concentration of pigments varied, from 1% to 26%, for 3 pigments sets (Stapa, Iriodin, Xirallic), and on two achromatic backgrounds (black and white). From the visual results for both geometries and illumination levels, two trends are observed. For the 15ºas15º geometry and for both illumination levels, with increasing pigment concentration, the detection distance decreases. This trend is more pronounced on the black background, although on the white background similar results are obtained.

In contrast, for the 45ºas45º geometry, the results are different compared to the 15ºas15º geometry and there is a dependency with the lightness value. For black background, it was found that for lower concentrations, the sparkle detection distance is smaller for large concentrations than for low concentrations. However, on white background, as the concentration is increased, the sparkle detection distance increases.

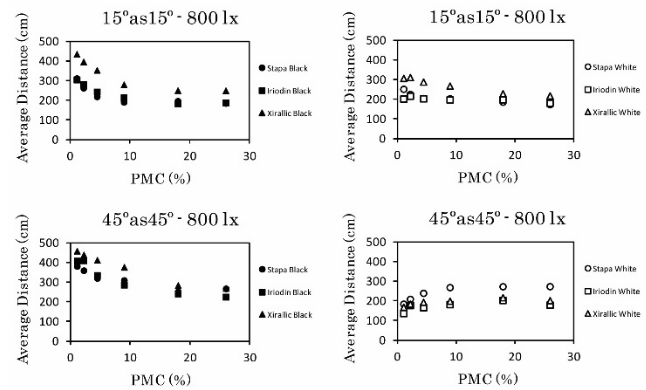

Figure 7. Sparkle detection distance vs Pigment concentration for low illumination levels (800 lx).

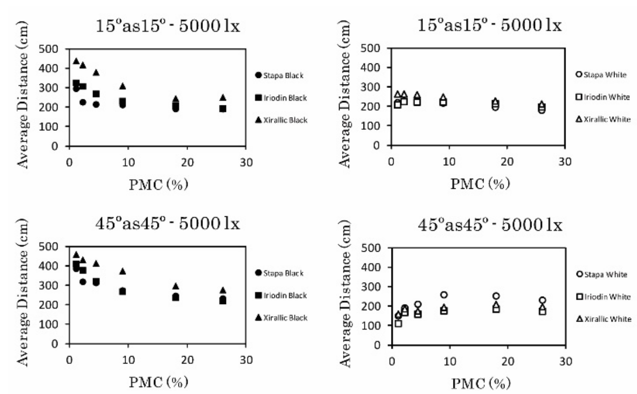

Figure 8. Sparkle detection distance vs Pigment concentration for high illumination levels (5000 lx).

Experiment 5: Visual and instrumental correlation: algorithm proposed by the CSIC Optics Institute (IO-CSIC) versus instrumental measurements provided by the BYK-mac

Two different devices were used to characterize the sparkle effect. Firstly, the BYK-mac multi-angle spectrophotometer was used, which provided three different values (sparkle intensity, area and grade) at different measurement geometries. Secondly, the GEFE gonio-spectrophotometer was also used, which provides two different values (intensity and contrast) under different measurement configurations. The total number of samples measured was of 100 with different special-effect pigment (Xirallic, Luxan, Silverdollar, Cornflake, etc) from different providers. To evaluate the correlation, the relationship was studied by trying to establish a linear relationship between variables associated with different equipments.

It was observed that there is a group of samples, in this case corresponding to Luxan and Xirallic pigment types, which shows a different behavior from the rest. These pigments have a high intensity variable value, which makes them stand out with respect to the rest of pigments which we see more grouped, making these pigments very novel within the automotive sector.

Analyzing the data for the three geometries it is observed that there is no inter-instrumental correlation (Figure 9). The reason for these results is that there are certain samples groups, which due to the pigments type (Xirallic, Luxan) that make up the coating formulation, they have a different behavior than expected, and that should be the subject of a more specific study in the future.

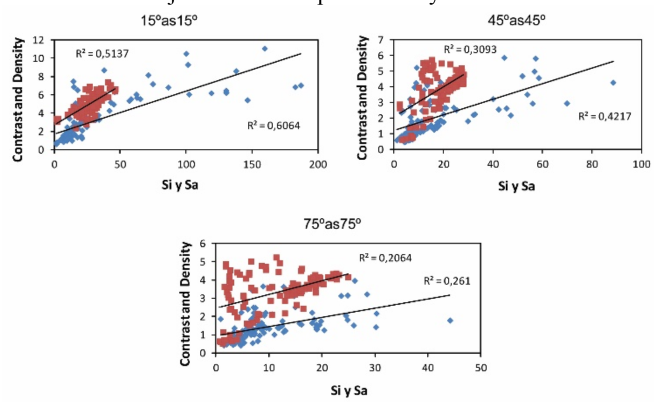

Figure 9. GEFE contrast and density variables vs BYK-mac sparkle intensity and area variables.

As for the visual and instrumental correlation of the whole set of samples, it was not possible to perform this analysis for the data provided by the GEFE, since the mathematical model does not generate a general sparkle value for each sample as BYK-mac does, the so-called S_G,. Instead we compared the instrumental data provided by the BYK-mac, along with visual assessments made by observers for each geometry and illumination level, divided into two large blocks according to the psychophysical experiment carried out, in this case detection distance and magnitude estimation of the sparkle texture effect, obtaining the following results:

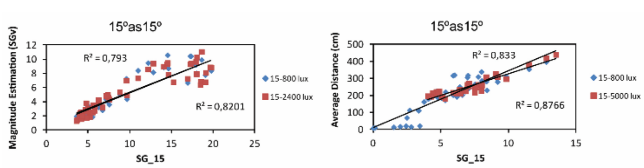

Figure 10, Instrumental and visual correlation of all samples analyzed with the BYK-mac for the geometry of 15ºas15º.

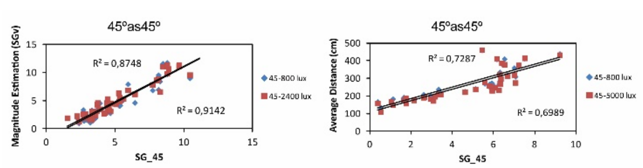

Figure 11, Instrumental and visual correlation of all samples analyzed with the BYK-mac for the geometry of 45ºas45º.

Conclusions

This work demonstrates the influence of many variables in the sparkle detection. Particularly, the variables studied were structural, environmental or colorimetric variables. Different visual experiments were conducted by considering previously the statistical design of experiments to optimize the visual experiment and to find better conclusions. In this way, it is found the pigment shape has more influence than the size pigment. Secondly, different environmental variables were studied as illumination level, correlated color temperature of the light source and measurement geometry. It was found that, for low illumination levels (800 lx) and 45ºas45º geometry, the sparkle can be detected at a greater distance. Finally, the pigment concentration was evaluated in the sparkle detection and a different behavior is found according the measurement geometry. In 15ºas15º measurement geometry, by increasing the pigment concentration, the detection distance is decreasing. On the contrary, for 45ºas45º measurement geometry, the change on the detection distance depends on the background. Therefore, the influences of all these variables make the sparkle effect a very complex subject to study because many variables have to be simultaneously considered. Thus, to develop a consistent and reliable algorithm that accurately reproduces the texture effect perceived by our eye is complicated, since there are numerous variables that an instrument can never take into account and that can only be evaluated in a psychophysical way.

Acknowledgements

We would like to thank the Ministry of Economy and Competitiveness for the coordinated project "New developments in visual optics, vision and color technology" (DPI2011-30090-C02), and the new project DPI2015-65814-R. Omar Gómez would also like to thank the Ministry of Economy and Competitiveness for his pre-doctoral fellowship grant (FPI BES-2012-053080).

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