Perception of sparkle in anti-glare display screens

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Abstract — In this paper, we describe a series of psychophysical experiments to quantify the relationships between anti-glare (AG) glass treatments and perceived sparkle in emissive displays. The experiments show the following: (1) that a new measure, pixel power deviation, correlates well with perceived sparkle; (2) that for a given AG treatment, sparkle is worse on high-pitch displays; (3) that tests of sparkle using small samples provide a conservative bound on perceived sparkle in display-sized samples; and (3) that sparkle visibility is affected by the content of displayed images. The goal of these efforts is to enable the development of AG glass treatments for emissive displays that effectively reduce front surface reflections while preserving high image quality.

Keywords *— display systems, sparkle.*

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1 Introduction

Modern electronic displays are typically composed of pixelated emissive elements (LCD/backlight, organic light-emitting diode, etc.) faced with a cover sheet of plastic or glass. This cover sheet can be designed to have a range of transmissive and reflective properties, and one common purpose is to reduce the visibility of reflections (glare) from light sources and the environment. Anti-glare (AG) treatments can be applied to the cover sheet that diffuse the reflections and thereby reduce their visibility. While these treatments can be effective in reducing the impact of surface reflections, they can sometimes produce a transmission artifact known as "display sparkle" where the displayed image appears to be covered by small colored highlights that scintillate with movement of the display and observer. Figure 1 shows a photograph of the sparkle phenomenon and Fig. 2 illustrates its cause. Sparkle artifacts can be disturbing and can severely reduce perceived image/display quality. Therefore, display designers have been trying to understand sparkle and to develop methods for minimizing sparkle in displays with AG treatments.

2 Prior work

Recently, a number of researchers have attempted to quantify sparkle and to relate it to the physical properties of AG surface treatments.

Cairns and Evans[1] observed that sparkle is similar in appearance to the speckle patterns seen when coherent laser light is transmitted by diffusing surfaces. They further observed that sparkle depends on the relative scales of the emitting and diffusing elements and the emitter to diffuser distance. Concluding that sparkle has the same cause as laser speckle, they suggest that a useful measure for characterizing sparkle is the standard (laser) speckle contrast ($\boldsymbol{SC}$) function

$$\boldsymbol{SC} = (\boldsymbol{\sigma_i}/\boldsymbol{I})$$

where $\boldsymbol{I}$ is the transmitted intensity and $\boldsymbol{\sigma_i}$ is the standard deviation of the transmitted intensity over the measurement region. In an experiment to verify this, they used a laser and a line-scan camera to measure the speckle contrast of two spray-produced AG surfaces with similar overall roughness values but with features at different spatial scales. For the surfaces they tested, they found that perceived sparkle was directly related to the measured speckle contrast.

Subsequently, Huckaby and Cairns[2] conducted a more systematic study of the relationship between speckle contrast and perceived sparkle. First, they measured the speckle contrast of five acid-etched AG surfaces having different roughnesses (as characterized by 60° specular gloss, with values ranging from 35 to 120). Then, they had 30 observers rate the perceived sparkle of the surfaces on a scale of 1–10 by placing them in front of a cathode-ray tube (CRT) and observing the effects. While they found that both speckle contrast and perceived sparkle increase monotonically with surface gloss (lower roughness), and suggest that this provides support for speckle contrast as a metric for perceived sparkle, the correlation (as seen in their results graph reproduced in Fig. 3) appears to be only modest.

Becker and Neumeier[3] took a different, image-processing-based, approach to characterizing sparkle. They started by arranging a monochrome digital camera in front of an liguid

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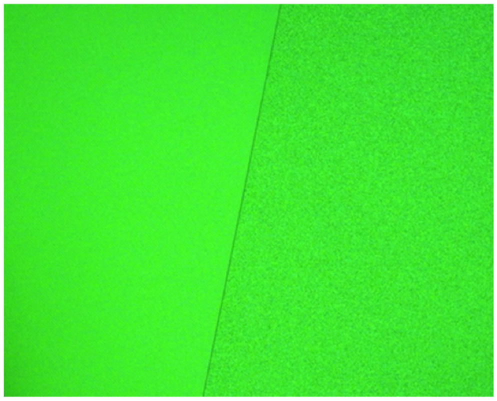

FIGURE 1 — Photograph showing the sparkle phenomenon. The left half of the image is a bare LCD panel displaying a uniform green image. The right half shows the same image seen through an anti-glare coating. Note the visible noise. In direct view, the dots appear to scintillate with movement.

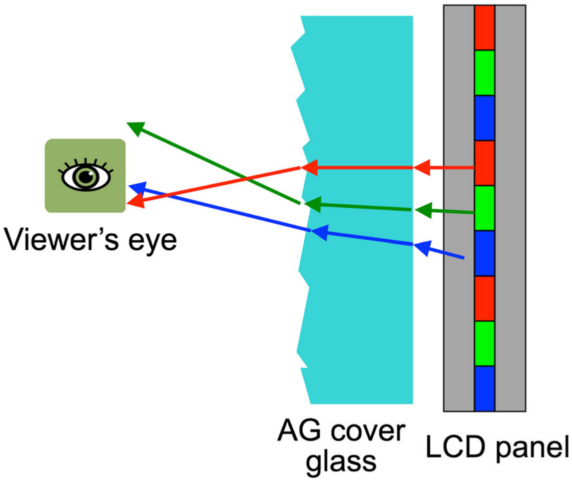

FIGURE 2 — Diagram illustrating the cause of sparkle. The rough surface of the anti-glare (AG) cover glass light rays emitted by the RGB subpixels in the LCD panel. This produces the sparkle patterns observed by the viewer.

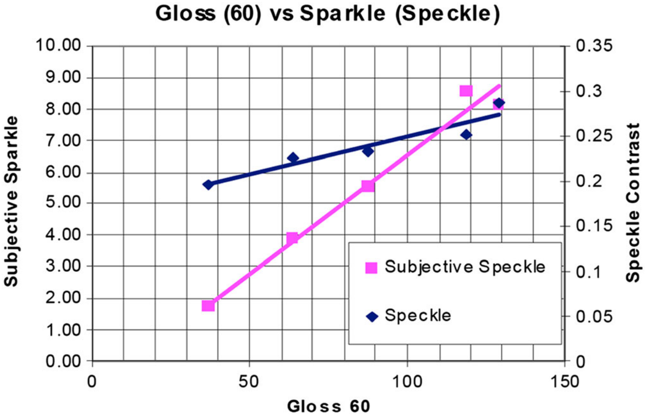

FIGURE 3 — Results of Huckaby and Cairns'[2] experiment relating 60° specular gloss, speckle contrast, and perceived (subjective) sparkle. While the speckle and sparkle functions are both monotonically increasing, the correlation only appears to be modest.

crystal display (LCD) display with an AG front surface. The camera and display distance were adjusted so that there were 5–7 camera pixels per display sub-pixel (RGB) and showed a uniform green image on the display. They then used two methods to characterize sparkle. In the "difference" method, they took two images of the display with the AG surface in different positions. They then took the difference between the image values, which eliminated constant intensity levels and revealed the intensity variations produced by the AG surface. In the second "spatial filtering" method, they took a single image and computed the intensity variations by dividing the measured image values by a low-pass filtered (averaged) version of the same image. To test the methods, they conducted an experiment in which they had expert observers place 14 AG samples into eight categories. They found good, near-linear relations between the image-based measures and perceived sparkle ratings, although the relations found using the difference method was more consistent than the spatial filtering method. They then investigated the relationships between three important properties of AG surfaces (glare reduction, distinctness of transmitted image, and perceived sparkle) and found that it is possible to design AG treatments that are high in the first two positive properties (glare reduction and distinctness of image) and low in the negative property (sparkle as measured by their methods).

Finally, in a project related to this one, Gollier *et al.*[4] have developed a new measurement device and metric for characterizing AG surface properties and perceived sparkle called pixel power deviation (PPD). The measurement device is illustrated in Fig. 4. In the device, a test sample is placed a set distance (typically 0.5 mm) from an RGB LCD display (Lenovo U110 notebook computer display) with its protective cover removed. The display is set to show a uniform green screen (only green subpixels illuminated). The light transmitted by the sample is imaged on a monochrome CCD (charge-coupled device) camera through a pair of lenses (L1 and L2) and is stopped by a diaphragm (D) with aperture set to 12 mrad to mimic the acceptance angle of the human eye. The optics are designed so that each LCD pixel is sampled by approximately 20 × 20 CCD pixels.

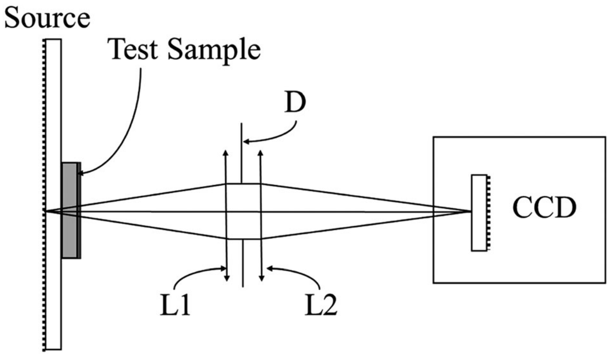

FIGURE 4 — Diagram of pixel power deviation measurement device. The "source" is an LCD panel showing a uniform green screen. The "test sample" is the anti-glare sample. "L1 and L2" are lenses, and "D" is diaphragm set to mimic the acceptance aperture of the human eye. The "CCD" is a scientific grade monochrome CCD camera. The optics are arranged so each LCD pixel is sampled by approximately 20 × 20 CCD pixels.

To measure the PPD of an AG sample, two images are captured, a test image of the screen seen through the sample and a reference image of the screen alone. To calculate the PPD of the AG sample, any dark noise or other background light is first subtracted from both the test and reference images, the pixel areas are identified, and the total power within each pixel is integrated. The pixel power distribution in the test image is normalized by dividing by the pixel powers from the reference image. The standard deviation of the distribution of these normalized pixel powers is then calculated to give the (referenced) PPD (PPDr) measure. Performing the measurement using a reference is necessary to remove any source non-uniformities and provide the sparkle level that arises solely from the sample under test. Figure 5 shows two images taken with the device.

To test the usefulness of the PPDr measure, in an unpublished experiment, Gollier *et al.*[4] asked observers to rate the perceived sparkle of 10 textured glass AG samples using a categorical rating procedure. They found excellent linear correlation between PPDr and perceived sparkle and in addition were able to estimate the absolute threshold for perceived sparkle at 1–3% PPDr.

While this work represents some promising first steps toward characterizing perceived sparkle and relating it to the optical properties of AG surfaces, perceived sparkle is not a fixed property and is known to vary with a number of display, environmental, and user-related factors. In this paper, we conduct a series of psychophysical experiments that investigate some of these factors to gain a fuller understanding of the sparkle phenomenon and to provide guidelines for the design of effective, high-quality, AG display treatments.

3 Experiments

In the previous section, a number of methods were described that attempt to characterize the potential sparkle of AG display surfaces. These methods use a variety of physical instruments and image processing techniques in laboratory settings to quantify the relationships between the optical properties of the surfaces and potential sparkle. While the methods represent a step forward in quantifying sparkle, the assessments made under highly controlled laboratory conditions may not fully predict the effects under typical use conditions where different kinds of displays (desktop, mobile, and television), with different resolutions (typically 75–300 ppi), will be showing different kinds of content (text, graphics, photos, and video) to users with different experiences, purposes, and preferences. To develop a better understanding of how these different factors affect perceived sparkle and the visual quality of displays with AG treatments, we have conducted a series of psychophysical experiments.

In experiment 1, we investigate the interactions of display resolution (pixel pitch) with perceived sparkle and quantify the relationships between perceived sparkle and the PPDr sparkle measure for displays with different pixel pitches. Because sparkle measurements are typically carried out on AG samples that are much smaller than the AG treated surfaces finally applied to the displays, in experiment 2, we study the effects of AG sample size on perceived sparkle and again relate the visual assessments to the PPDr sparkle measure. Finally, in experiment 3 we look at the effects of image content on perceived sparkle for range of representative content including photographic landscapes and portraits, and text, as well as standard test images. The methods, procedures, and results of the experiments are described in the following sections.

3.1 Methods

Modern emissive displays have a wide variety of pixel geometries and sizes. These factors are known to affect the sparkle phenomenon, with sparkle generally understood to be more problematic as display resolution increases or rather as pixel pitch decreases.[1] To investigate this issue and to provide data relevant to modern systems, we studied two displays. The first was an LCD panel from a Lenovo U110 laptop computer with its protective cover removed. The LCD panel had square pixels, RGB subpixels, and a pixel pitch of 141 pixels/in.

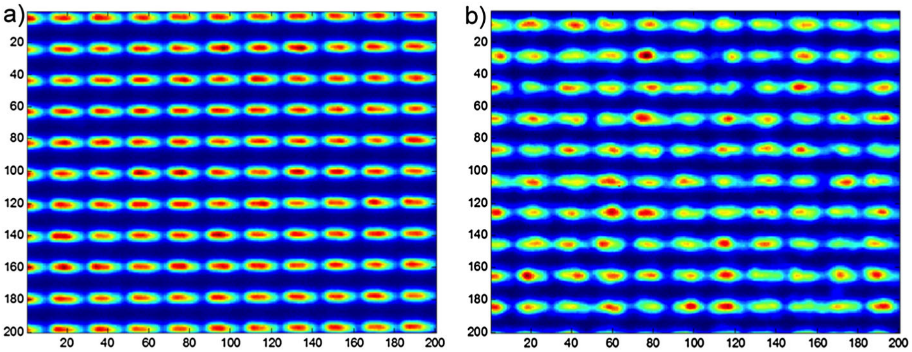

FIGURE 5 — False color images of anti-glare samples acquired with the pixel power deviation (PPD) measurement device. The sample imaged in Fig. 5a does not exhibit any visible sparkle and has pixel images that are regular and consistent, yielding low referenced PPD (PPDr). In contrast, the sample image in Fig. 5b shows higher variation in the pixel power distributions yielding higher PPDr and higher visible sparkle.

(180 μm/pixel). The other display was a "Retina" LCD panel from an Apple iPad 3 tablet computer. This display also had square pixels and RGB subpixels but had a finer pixel pitch of 264 pixels/in. (95.2 μm/pixel). We tested this display with its glossy cover glass/touch screen in place.

To study the effects of different AG treatments, we created a set of AG glass samples by roughening the front surfaces of 0.7-mm-thick alkali aluminosilicate glass through various etching processes. Different surface roughnesses were produced by varying the treatment times. Separate reference and small (2 in. × 2 in.) and large (6 in. × 6 in.) sample sets were created. We measured the light-scattering properties of the samples using the PPDr technique described earlier. The PPDr measurements were referenced to the Lenovo LCD panel. The measured PPDr values for the sets of AG glass samples used in the experiments are given in Tables 1 and 2.

3.2 Procedure

We performed a series of psychophysical scaling experiments to understand the relationships between the properties of AG display glass and perceived sparkle. All the experiments used the same graphical rating procedure.[5]

The experimental setup is shown in Fig. 6. The "small" glass samples were glued to the backs of 35 mm slide mounts, which provided a standard viewing aperture (one 3/8 in. × 7/8 in.) and allowed for easy handling of the samples without smudging. The samples were placed directly against the display being tested with the AG surface closest to the viewer. Four "reference" samples with PPDr values 0.6, 4.2, 7.7, and 12.1, were placed in a row along the bottom of the display from low to high (left to right). The "test" sample being evaluated was placed above the row of reference samples. Observers viewed the samples from approximately 18 in. under normal office lighting conditions; however, care was taken to avoid front surface reflections from the glass samples.

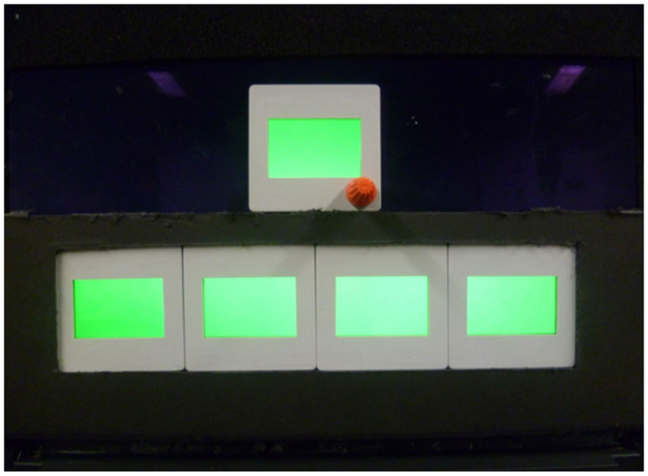

FIGURE 6 — Setup used in the sparkle scaling experiments. LCD panel showing a uniform green screen is behind a black cardboard mask. Reference samples glued to 35 mm slide mounts form a scale that is along the bottom (low to high referenced pixel power deviation, left to right). The test sample, with placement handle, is on the top. Although not evident from the photograph, the level of sparkle varies significantly across the scale.

TABLE 1 — Referenced pixel power deviation values of the reference samples and the "small" test samples used in experiments 1 and 3.

"Small" samples	PPDr value
Reference 1	0.6
Reference 2	4.2
Reference 3	7.7
Reference 4	12.1
Test 1	0.7
Test 2	1.0
Test 3	2.5
Test 4	3.1
Test 5	4.0
Test 6	5.2
Test 7	5.2
Test 8	6.4
Test 9	7.1
Test 10	8.8

PPDr, referenced pixel power deviation.

TABLE 2 — Referenced pixel power deviation values of the "large" test samples used in experiment 2.

"Large" samples	PPDr value
Test 1	0.4
Test 2	2.2
Test 3	4.4
Test 4	5.8
Test 5	8.0

PPDr, referenced pixel power deviation.

On each trial of an experiment, observers were given a sheet of paper with a 6-in. line printed on it (Fig. 7). Cross marks made at four intervals across the line were used to represent the magnitudes of the reference samples. For each test sample, observers were asked to make a mark on the line to indicate how the sparkle of the test sample compared with the sparkle of the reference samples. Note that while the reference and test samples were characterized using the PPDr measure, the measured values and choice of reference stimuli placed no necessary constraints on the observers' judgments of perceived sparkle for a given sample. Observers were free to rate the test samples as they saw fit, and thus, an infinity of potential psychophysical relations were possible.

To calculate the observer's rating (s), the distance (d) from the left edge of the line to the mark was divided by the total line length (6 in.), and then, this value was multiplied by the sum of the lowest and highest reference PPDr values $[s = d/6^{*}(0.6 + 12.1)]$. These ratings were then averaged across the

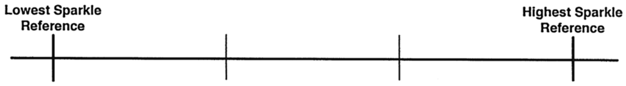

FIGURE 7 — Response figure used by the observers in the scaling experiments. Cross points indicate the magnitudes of the reference samples. Observers were instructed to make a mark at the scale location corresponding to the perceived sparkle of the test sample. Sparkle ratings were calculated from normalized mark/scale distances.

observers tested, to calculate an overall perceived sparkle value for each test sample. We applied this linear scaling to the data so the PPDr and perceived sparkle scales would have the same numerical range; however, because the rating method produces *interval* scales, all linear scalings of the data are equivalent, and while the range of the scale and stimulus scale values may change, the relationships (distances) between the stimuli measured with respect to the scale are preserved.

Twenty male and female observers aged 18–35 years participated in the experiments. All were university students or employees. Some had professional interest in imaging systems, but all were naïve to the specific topics and purposes of the experiments. All had normal or corrected-to-normal vision.

3.3 Experiment 1: effects of display characteristics

In experiment 1 we wanted to investigate the effects of display pixel pitch on perceived sparkle. To do this, we had observers scale the sparkle of the small AG samples on the low-pitch and high-pitch displays described earlier, using a uniform green screen as a background image. The results of the experiment are summarized in Fig. 8, which plots perceived sparkle versus measured PPDr. The two sets of glyphs show the results for the two displays tested. The error bars indicate the standard deviations of the ratings, and the lines and equations are regression fits to the data.

Two main findings can be seen in the graph. First, on each display, there is a strong linear relationship ($R^2 = 0.97$) between sample PPDr and perceived sparkle. This suggests that PPDr is potentially a good predictor of sparkle for AG treatments. Also, it is important to note that although PPDr is measured on the 141 ppi display, the perceived sparkle on the higher resolution display still scales linearly with the measured values. This suggests that PPDr values can be scaled using a multiplier related to the pixel pitch, or other systems parameter, to provide a relative magnitude of sparkle for other displays. Second, an analysis of variance showed that the slopes of the PPDr versus sparkle lines are significantly different for the two displays ($df = 1$, $F = 83.98$, $p < 0.001$). The data show that over most of the PPDr ranges, the sparkle ratings for samples test on the high-pitch display are greater than the ratings for samples tested on the lower-pitch display. This result confirms informal observations that for a given AG treatment, perceived sparkle increases with display pitch and shows that the effect is very systematic.

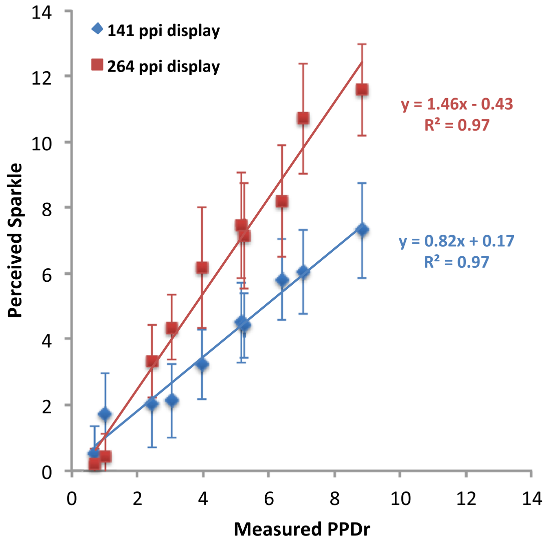

FIGURE 8 — Results of experiment 1—note the linear relationships between measured referenced pixel power deviation (PPDr) and perceived sparkle and that for a given anti-glare sample, perceived sparkle is higher on the high-pitch (264 ppi) display.

In addition to understanding the relationship between PPDr and perceived sparkle across the range of AG treatments on different displays, it is also useful to understand the relationships between measured differences in PPDr and differences in perceived sparkle. This information is valuable for establishing tolerances on manufacturing processes and for the optimization of sparkle with respect to other treatment properties. To investigate this issue, we analyzed the variance of the perceived sparkle ratings for each of the samples used in experiment 1 and estimated the just-noticeable difference in PPDr for the treatments we tested. To do this, we averaged the standard deviations of the sparkle ratings measured for each sample in experiment 1 and then multiplied this result by a factor of 0.67449 to reflect the standard 75% detection threshold used in visual psychophysics.[5] This calculation resulted in an estimated sparkle just-noticeable difference of 0.84 PPDr units. In practical terms, this means that a measured PPDr difference of this amount should be detectable on three out of four observations. While this finding is in line with our informal observations and the fact that samples represented significant ranges of both AG properties and perceived sparkle, it must be emphasized that this is only a rough estimate, and formal sparkle discrimination studies should be performed to establish more reliable measures.

3.4 Experiment 2: effect of sample size

In experiment 2, we wanted to understand if sparkle measured using small samples would be a good predictor of sparkle in larger mobile display-sized (smart phones and tablets) treatments. This is an important question because in-lab testing is often used to provide specifications and tolerances for commercial production and manufacturing. The methods and procedures used in experiment 2 were the same as those of experiment 1, but the "large" AG samples were tested. In this case, to approximate the slide mounts used for the samples in experiment 1, the larger samples were affixed to the backs of square, black cardboard panels with 3.5 in. × 5 in. apertures. The reference samples and apparatus were the same ones used in experiment 1. Only the high-pitch 264 ppi display was used in testing.

The results of experiment 2 are plotted in Fig. 9. The data from experiment 1 for the small samples on the high-pitch

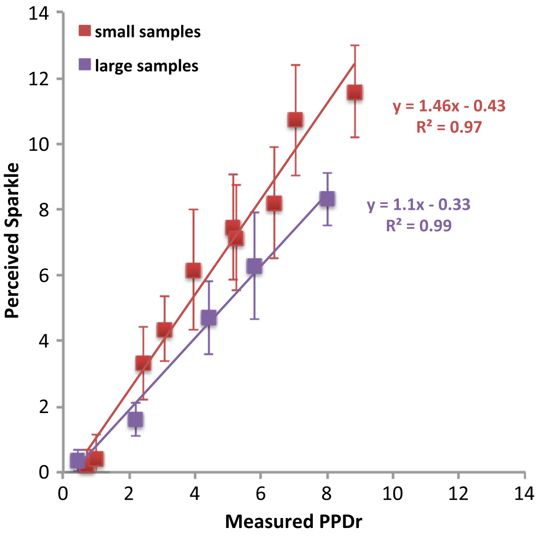

FIGURE 9 — Results of experiment 2—note that perceived sparkle measured using the small samples is a conservative predictor of sparkle for the larger display-sized samples.

display are plotted for comparison. As in experiment 1, the PPDr versus sparkle ratings for the large samples show a strong linear relationship ($R^2 = 0.99$), suggesting that PPDr is a good metric for perceived sparkle in AG display treatments. The graph also shows that for a given PPDr value, perceived sparkle for the large samples is lower than for the small samples, but an analysis of variance showed that the differences are not statistically significant ($df = 1$, $F = 0.29$, $p = 0.59$). The results suggest that in-lab sparkle testing using small samples will likely be a conservative predictor of perceived sparkle in mobile display-sized AG treatments and that therefore the PPDr metric may be useful for establishing specifications and tolerances in commercial production and manufacturing.

3.5 Experiment 3: effects of image content

In experiment 3, we studied the effects of image content on perceived sparkle. This is an important question. While AG display treatments are typically evaluated in-lab using abstract test patterns such as green screens, these patterns are not necessarily representative of the kinds of images end users will show on the displays. Furthermore, testing may overestimate or underestimate perceived sparkle under typical use conditions, leading to unnecessary constraints and expenses for manufacturers and/or dissatisfied end users. To investigate this issue, we had observers scale the perceived sparkle of AG samples while viewing real images. To represent the kinds of image content end users might display, we created an image set that included typical photographic images (landscape, portrait, and crowd) as well as text. The images used in the experiment are shown in Fig. 10. The small samples and the high-pitch display were used. All the images were rendered at the native resolution of the display. Otherwise, the experimental methods, procedures, and observers were the same as the ones used in the two previous experiments including the reference samples backed by uniform green image.

The results of experiment 3 are shown in Fig. 11. As in experiments 1 and 2, linear trends were seen between measured PPDr and perceived sparkle across the range of AG samples; however, the data also show that image content can have a significant impact on perceived sparkle. First, note that with one exception, the sparkle ratings obtained with the green patch are the highest at each PPDr level. Second, note that

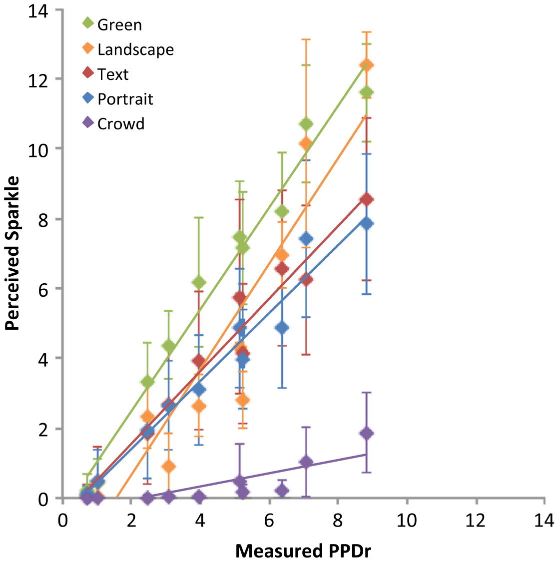

FIGURE 11 — Results of experiment 3—note that with the exception of the "landscape" image at high referenced pixel power deviation values, samples tested with real images show lower perceived sparkle than those tested with a green screen. This suggests that green screen testing is conservative but may be excessive for typical use contexts. In particular, perceived sparkle for samples tested with the busy "crowd image" image was near negligible across the full sample range, suggesting that visual masking effects may significantly reduce the visibility of sparkle under some conditions.


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FIGURE 10 — Images used in experiment 3. (Left to right) text block sample, landscape, portrait, and crowd image.

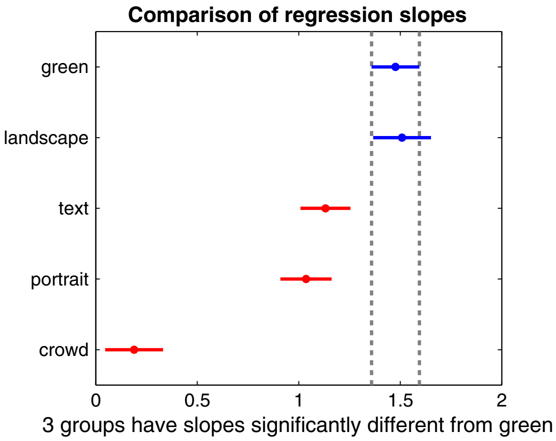

FIGURE 12 — Analysis of experiment 3—results of a multiple comparison test on the slopes of the regression lines for the data shown in Fig. 11. Note that the slopes of "perceived sparkle" functions for the text and portrait images are significantly lower than those for the green and landscape images ($p < 0.001$) and that the slope of the function for the crowd image is significantly lower than all of the others ($p < 0.001$).

testing with the text block sample, portrait, and crowd image images showed significantly lower sparkle ratings than testing with the green patch [$p < 0.001$ in each case as measured by differences in their regression slopes with respect to the green patch data (Fig. 12)]. Third, note that in particular, the sparkle ratings for samples tested with the visually busy crowd image were near negligible across the full PPDr range, likely due to visual masking effects.[6] Finally, note that the landscape image showed some nonlinearity, with low sparkle ratings for low-to-moderate PPDr values and high sparkle ratings at high PPDr values. Taken together, these results suggest that while the current practice of evaluating AG display treatments with green screens is likely to be a conservative predictor of perceived sparkle, in many cases, it may lead to overly stringent requirements that may negatively impact other aspects of product production (such as cost and rejected units) and end user performance (such as image contrast and sharpness).

4 Discussion and conclusions

In this paper, we have described a series of psychophysical experiments that explore the relationships between the properties of AG glass treatments and perceived sparkle in emissive displays. The experimental results show the following: (1) that a new measure of sparkle, PPDr, correlates well with perceived sparkle; (2) that sparkle is affected by interactions between AG treatments and display pitch, with sparkle appearing worse on high-pitch displays; (3) that tests of perceived sparkle made using small samples provide a conservative bound on sparkle in display-sized samples; and (4) that sparkle visibility is affected by the content of displayed images, with solid green screens typically rated as showing the most sparkle, photographic and text images rated as showing somewhat less, but with busy images rated as showing significantly less sparkle, probably due to visual spatial-frequency masking effects.

While these results are promising and useful, there is still much work to be done. First, the glare-reducing properties of glass samples should be evaluated and compared with sparkle measures to understand trade-offs in these factors. Second, the effects of image content should be studied more systematically to allow sparkle to be predicted under typical use conditions. Finally, the effects of motion on perceived sparkle (whether from dynamic content or from observer/device movement) should be studied. Together, these efforts should allow the development of psychophysical models of the effects of AG glass treatments that should enable the production of emissive display systems that provide high image quality under widely varying viewing conditions.

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