Brightness of the Glare Illusion

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(a) "Vendor with Pheasant by Candlelight" by Petrus van Schendel.

(b) Sunset in Niigata, Japan.

(c) Screenshot from "Alan Wake" by Remedy Entertainment.

Figure 1: *Glare illusion in painting, photography, and computer graphics respectively from left to right.*

Abstract

The glare illusion is commonly used in CG rendering, especially in game engines, to achieve a higher brightness than that of the maximum luminance of a display. In this work, we measure the perceived luminance of the glare illusion in a psychophysical experiment. To evoke the illusion, an image is convolved with either a point spread function (PSF) of the eye or a Gaussian kernel. It is found that 1) the Gaussian kernel evokes an illusion of the same or higher strength than that produced by the PSF while being computationally much less expensive, 2) the glare illusion can raise the perceived luminance by $20 - 35\%$, 3) some convolution kernels can produce undesirable Mach-band effects and thereby reduce the brightness boost of the glare illusion. The reported results have practical implications for glare rendering in computer graphics.

CR Categories: I.3.8 [Computer Graphics]: Applications—[I.4.9]: Image processing and computer vision—Applications

Keywords: Glare illusion, Human Visual Systems (HVS), Psychophysics

1 Introduction

The glare illusion has been efficiently used for boosting the brightness of light sources in paintings, exploited in photography, and commonly employed in computer games (see Figure 1 from left to right, respectively). The illusion can evoke a very realistic sensation of self-luminous objects and can produce an impression of higher brightness than the maximum of a computer display or reflectance of white paint. While painters have to rely on their skill to produce the glare illusion, glare in photography arises naturally as the result of light scattering in lenses (referred to as *lens flare*) and can be further enhanced by cross screen or diffusion filters.

A large number of papers in computer graphics have proposed advanced visual models (diffraction and diffusion in the eye optics) to generate a realistic glare illusion [Nakamae et al. 1990; Rokita 1993; Spencer et al. 1995; Ward Larson et al. 1997; Kakimoto et al. 2004; Kakimoto et al. 2005]. However, both painters and photographers have been able to produce stunning glare illusions without any knowledge about the optical effects in the eye. Accurate visual models are also rarely used in practice, for example in game engines, as they are computationally too expensive. Instead, game artists hand-tune their digital filters to produce the best effect, even though the resulting convolution kernel is very different to the actual visual models. In this paper, we compare both approaches: an ad-hoc approach that involves the convolution with a Gaussian filter, and a physically-based approach that employs a Point Spread Function (PSF) of the eye. We measure the brightness boost that can be achieved with both methods and discuss the problems that may arise, such as deformation of the "glaring" objects due to clipping of high pixel values and undesirable Mach-band illusion that forms a bright outline around the modified objects.

It should be noted, that the glare illusion we investigate in this paper is different from disability glare and the illusionary glare effect. The glare effect consists of an illusionary glow (blooming), concentric rings of different colors (corona) and radial streaks (flare) that we can observe around bright objects and light sources. The glare effect causes the so-called disability glare, which is the loss of contrast visibility in the presence of strong light sources. The glare illusion on the other hand evokes an illusion in the center of an object rather than in its surround as the presence of a smooth gradient around an object can cause the object to appear brighter and self-luminous.

2 Previous Work

Nakamae et al. introduced a rendering technique by considering diffraction effects at the pupil and eyelashes in images with high

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intensity lights [Nakamae et al. 1990]. Rokita proposed a technique to render high intensity lights, blooming and glare [Rokita 1993]. His method dealt with the spectrum of the incoming light and diffraction at the lens and on particles in the eye. Spencer et al. presented a quantitative model to render glare [Spencer et al. 1995]. They reviewed the physical mechanism of glare and modelled it by a PSF for each of photopic, mesopic, and scotopic cases. They also reported that the glare effects enhance the brightness of light sources. Ward Larson et al. employed Moon and Spencer's adaptation model [Moon and Spencer 1945] in their tone reproduction operator to enhance bright objects [Ward Larson et al. 1997]. Kakimoto et al. attributed the main source of glare to the diffraction on the eyelashes and pupil and simulated it using wave optics [Kakimoto et al. 2004; Kakimoto et al. 2005]. Van den Berg et al. proposed a physical model to simulate the ciliary corona found by Simpson [Simpson 1953] that often accompanies the perception of real glare sources [van den Berg et al. 2005]. They assumed that the incoming light is scattered on small particles situated in the lens and the vitreous in the eye.

All of the above methods render glare effects by simulating optics of the eye. Kawase proposed a method to render glare by combining several Gaussian convolutions with different kernel sizes [Kawase 2005]. This method has no perceptual background, still, since this approach is simple and computationally inexpensive, it is often used in computer games.

Although much attention was put to physical and optical aspects of the glare effects and modelling disability glare [Vos 2003], the brightness boosting glare illusion has not been well studied. Zavagno and Caputo conducted psychophysical experiments to measure the impression of self-luminosity of glare [Zavagno 1999; Zavagno and Caputo 2001]. They asked subjects to increase the gradient of ramps between a bright patch and four surrounding dark squares until the center patch started being perceived as self-luminous. They found that there was a linear relation between the background luminance and the ramp gradient.

The glare illusion often coexists with other illusions, which can either raise or lower perceived luminance. *Simultaneous contrast* causes a perceptual shift in color appearance when the color of the stimulus background is changed [Gerrits and Vendrik 1970; Adelson 1993; Fairchild 1998]. A stimulus is perceived as darker on a light background while the same stimulus is perceived brighter on a dark background. Furthermore, the steep gradient of the glare profile and its abrupt termination by clipping can elicit the *Mach-band* illusion [Ratliff 1965; Lotto et al. 1999], which is visible as a bright outline around the glaring object. Finally, the convolution kernel used to produce glare can cause an object to grow or to change shape (see the first column of Figure 3), which results in an increase of brightness, since larger objects often appear to be brighter [Li and Gilchrist 1999].

3 Stimuli and Apparatus

We conducted a psychophysical experiment to measure the boost in brightness caused by the glare illusion. The input images used in our experiments consisted of a disk (0.3 vis deg) displayed on a background image (3.2 vis deg) containing a cloudy sky. The complex background introduced both contrast and context, which was more natural setting than a flat background. The average luminance of the background was 150 cd/m^2. A reference image with the glare illusion rendered around the disk was shown in the center and two target images without any glare were presented on both sides, as shown in Figure 2. The maximum luminance of the reference image L_{dmax} was kept constant at 220 cd/m^2 (the maximum luminance of a typical display), but the disk luminance of the target images could be increased up to the maximum luminance of the display used for the experiment (433 cd/m^2).

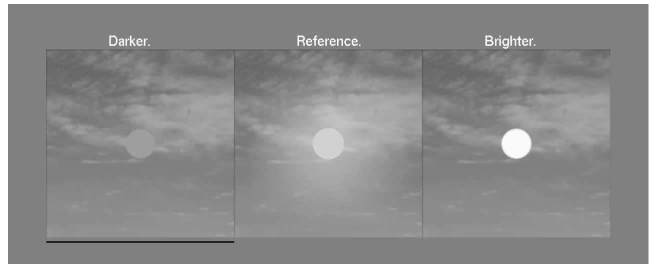


Figure 2: *Screenshot of a single trial of the experiment. A reference image (middle) and two target disks (left and right) are shown at each trial. The subject was asked to adjust the luminance of the disks in the target images to "slightly but visibly darker" (left) and "slightly but visibly brighter" (right). The thin black line below a target image indicates which target disk patch is currently selected for adjustment.*

The images were displayed on a 20.8″ 10-bit LCD display (Barco Coronis Color 3MP Diagnostic Luminance). The 10-bit precision eliminated potential contouring artifacts on smooth gradients, which could have been observed on an 8-bit display. The Barco display was carefully calibrated by measuring its luminance response for a range of input values using the MINOLTA LS-100 light meter.

To generate the glare illusion for the reference image, we used two strategies: a method that employed Gaussian convolution, commonly used in game engines (Method I); and the method proposed by Spencer et al. [Spencer et al. 1995] that employs a PSF of the human eye (Method II). Our input is a linear luminance image L (not gamma corrected). In both methods, we first compute for each pixel the luminance that exceeds the maximum luminance of a typical display L_{dmax}:

$$\Delta L = \begin{cases} L - L_{dmax} & \text{if} \quad L > L_{dmax} \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

Next, ΔL is convolved with an appropriate 2D digital filter. There are two reasons for applying convolution only to the values greater than L_{dmax}: firstly, we do not want to blur the entire image; and secondly only the pixels whose luminance can not be displayed should be boosted in brightness. For Method I, the convolution kernel is given by

$$F(x, y) = \frac{1}{k} \exp\left(-\frac{x^2 + y^2}{2\,\sigma^2}\right), \tag{2}$$

where x, y are pixel indices (from $-s/2$ to $s/2$, where s is the stimulus size), $\sigma = 0.34$ vis deg, and k is a normalization factor computed as the sum of all kernel elements. For Method II, similarly as in [Spencer et al. 1995], we employ the PSF proposed by Vos [Vos 1984]:

$$PSF(\theta) = 0.384\ f_0(\theta) + 0.478\ f_1(\theta) + 0.138\ f_2(\theta) \tag{3}$$

where θ is the angle between the primary object and the glare source in degrees and $f_0 \ldots f_2$ are:

$$f_0(\theta) = 2.61 \times 10^6 e^{-(\frac{\theta}{0.02})^2}, \tag{4}$$

$$f_1(\theta) = \frac{20.91}{(\theta + 0.02)^3}, \tag{5}$$

$$f_2(\theta) = \frac{72.37}{(\theta + 0.02)^2}. \tag{6}$$

We compute the digital filter by integrating the proposed PSF of the eye using trapezoidal numerical integration over ten samples for each pixel. The result of the convolution is added back to the original luminance map L and all values are clamped to the maximum value L_{dmax}. A lookup table generated by the MINOLTA LS-100 light meter for display calibration is used to map the resulting luminance values to the display pixel values. We generate stimuli of twice the resolution as required and then filter and subsample them to avoid aliasing artifacts.

To vary the strength of the glare illusion, the input disk luminance (L_{disk}) for the glare rendering is set to one of the six levels: 220, 1165, 2110, 3055, 4000, and 7000 cd/m^2 (labeled as "A" – "F") for Method I and 220, 1480, 2740, 4000, 7000, and 10000 cd/m^2 (labeled as "a" – "f") for Method II. Note that the L_{disk} parameter is abstract and the same value of this parameter can result in different strengths of the glare illusion for Methods I and II. However, we selected the values L_{disk} so that the stimuli "C" and "c" do not differ visibly in size from the original disk, and the entire usable range of this L_{disk} is examined. All reference images used in the experiment are shown in Figure 3.

4 Experimental Procedure

Although perceived luminance is usually measured using magnitude estimation, magnitude production, or brightness matching methods [Wyszecki and Stiles 1982, pp. 393, 492] [Graham 1965, pp. 230 – 233], we found that these procedures resulted in too high inter- and intra-observer variance, which made the data too noisy to interpret. One possible reason for the high variance is that the illusion is often subtle and not much larger than the discrimination threshold. To reduce the discrimination threshold, we increased the background luminance from almost black (1 cd/m^2) to a much higher level (150 cd/m^2) in our pilot studies. This should help to reduce the discrimination threshold, as it is known that it increases with the luminance difference between a background and a target disk [Whittle 1986]. We also increased the disk size and reduced the distance between reference and target images, as larger stimuli that are closer to each other are easier to compare. We experimented with temporal comparison, but dismissed this procedure because the measurements could be affected by the Gelb effect (see [Gilchrist et al. 1999] for details on the Gelb effect). To improve accuracy, we also tried to employ stricter procedures, such as two-alternative-forced-choice (2-AFC) combined with Parameter Estimation by Sequential Testing (PEST), but we did not observe a reduction in variance.

To further reduce the randomness in the subjective responses, subjects were asked to adjust the target images such that the perceived luminance of the left disk was as close as possible to that of the reference disk but slightly and visibly *darker*. Likewise, the right disk should be adjusted to be perceived as slightly but visibly *brighter*. Then, the matching perceived luminance is assumed to be the mean of both left and right target disk luminance, thereby producing a measure that is more robust against outliers.

When the Mach-band illusion was seen on the reference disk by the first look, the subject was asked to ignore the Mach-band as much as possible and adjust the target disks to the brightness inside the illusionary ring. As a hint of how to adjust brightness of target disks, a subject was instructed as follows: "You could try to adjust the brightness of the target disks as same as that of the reference and then go down/up until you start seeing the difference." Both target disks were initially set to significantly different luminance levels (100 and 400 $cd/m^2$for "darker" and "brighter" target images, respectively).

After adjusting the luminance of the target disks, a questionnaire followed each trial. All questions were asked for each reference image and could be answered by "yes" or "no" (see Table 1 for the details of the questions).

10 subjects (7 males and 3 females) at the average age of 30 (between 26 and 40 years old) participated in our experiment. All subjects were naïve about the purpose of the experiment and had either normal or corrected-to-normal vision. The subjects were seated at a distance of 1 m from the display under dim lighting condition (60 lux). Each subject read a written instruction of the experiment, passed a training session, and then took the main part of the experiment without repetition. Taking a training session for 5 minutes gave a subject enough time to be adopted for the lighting condition of the room. The whole procedure of the main experiment took approximately 20 minutes for a single subject.

5 Results

The results of our experiment averaged over the 10 subjects are plotted in Figures 4 and 5. As shown in Figure 5, the glare effect can raise the perceived luminance by $20 - 35\%$ compared to the actual luminance 220 cd/m^2, and Method I boosts the perceived luminance more than Method II. Apparently, perceived luminance levels increase with increasing luminance of the disk L_{disk} that enters both methods as the main parameter. The growing trend of perceived luminance as a function of L_{disk} does not appear to be linear: while small and medium values of L_{disk} have strong effects on perceived luminance, this effect saturates for large values of L_{disk}.

It is apparent from Figure 4, that the upper and the lower bounds of the perceived luminance do not differ qualitatively since the general shape of the curves are close to parallel in all cases. Therefore, the measuring accuracy can be increased by using the mean of these two thresholds instead of the two separate values. In the analyses reported in the following, only the mean of the two thresholds is used as a dependent variable.

To analyze the data, we conduct a 6 (disk luminance L_{disk}) $\times 2$ (method) Analysis of Variance (ANOVA), treating disk luminance and method as repeated measurement factors. Because the scale of the parameter L_{disk} is not comparable for the two Methods, the analysis treats different levels ("A" – "F" and "a" – "f" for Methods I and II, respectively) rather than numerical values of L_{disk} as equivalent. These values are assumed to be of ordinal scale. There is a significant main effect of L_{disk}, $F(5, 45) = 23.68, p < .001$, indicating that the luminance of the center disk (which entered the algorithms as the main parameter) has an influence on how bright it was perceived to be. The main effect of factor "Method" is not significant, $F(1, 9) = 1.64$, showing that the two Methods do not differ in brightness boost over all levels. However, the $L_{\text{disk}} \times$ Method interaction reaches significance, $F(5, 45) = 7.77, p < .001$, indicating that the Methods differ at some, or at least one, of the levels of L_{disk}.

To narrow down this effect, further analyses are carried out. From the visual inspection of the data (Figure 5), it is suspected that the two Methods differ only for large values of the parameter L_{disk}. Therefore, two ANOVAs which are similar to the one above are conducted for levels {A, B, C} and {D, E, F} separately. As expected, the main effect for "Method" in the ANOVA for the first group of levels {A, B, C} remains not significant ($F(1, 9) = 1.4$), while the Method factor reaches significance for the second group of levels {D, E, F} ($F(1, 9) = 11.96, p < .01$). There are no other significant effects, in particular the Method $\times L_{\text{disk}}$ interaction does not reach significance in both analyses ($F(2, 18) = 1.34$ and $F(2, 18) = 0.28$), indicating that the interaction effect from the global analysis is sufficiently explained by this separation. Pairwise *t*-tests of the two Methods for the levels D, E and F of L_{disk}

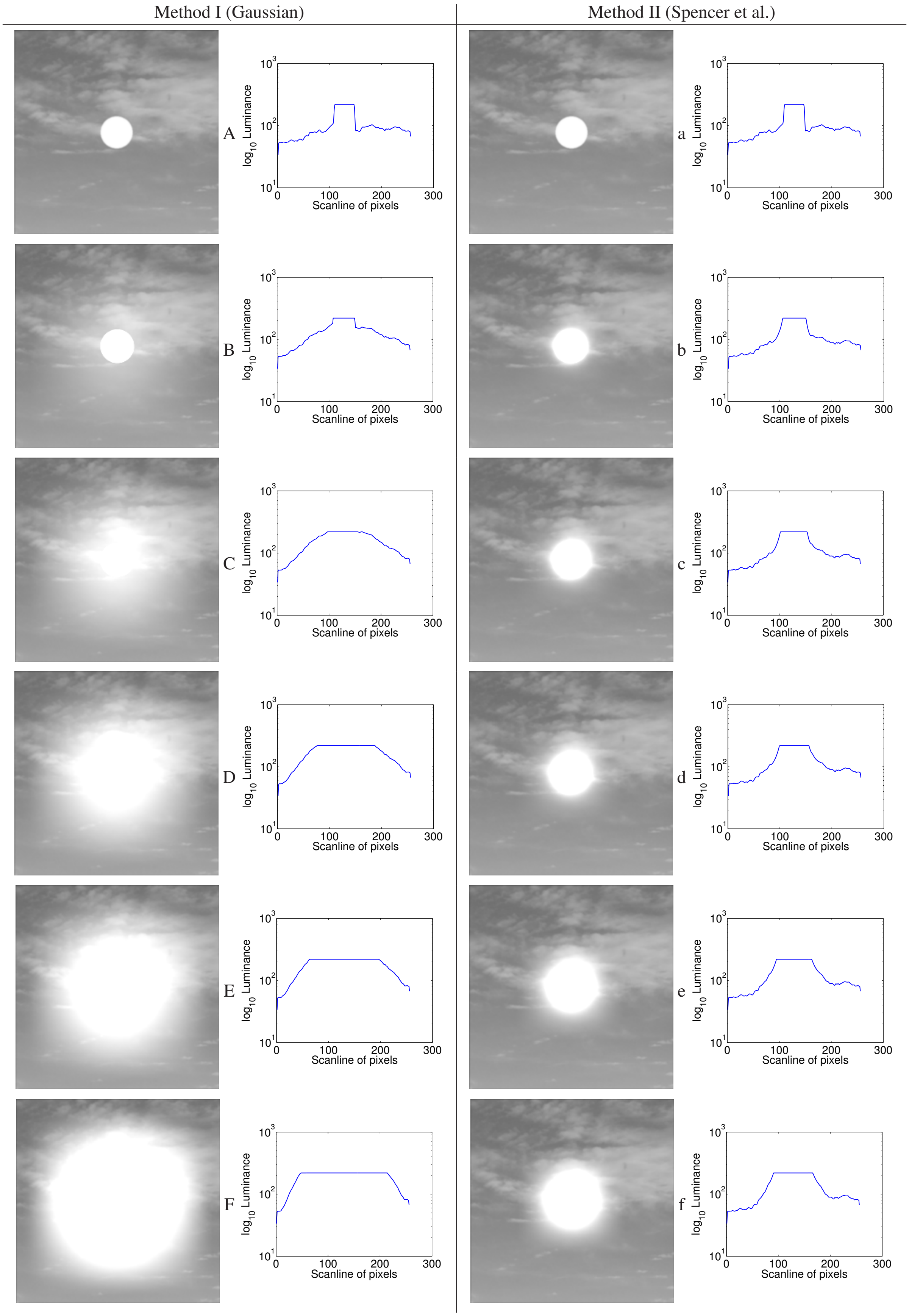
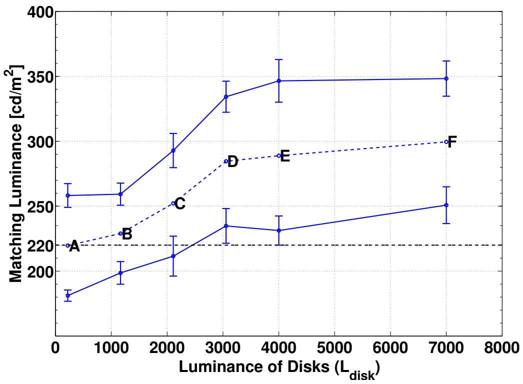
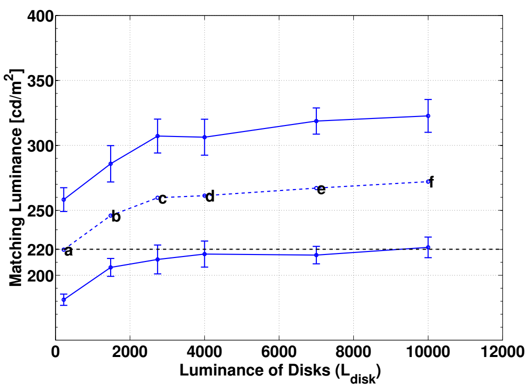


Figure 3: *Experimental stimuli and their profiles. The images in the left column show the stimuli and profiles for Method I (Gaussian), while those for Method II (Spencer et al.) are arranged at the right side. The characters between stimuli and profiles indicate the luminance of the reference disks L_{disk} (see Section 3 for details).*



(a) Method I (Gaussian)



(b) Method II (Spencer et al.)

Figure 4: *Results of our experiment averaged over 10 subjects. The upper and lower solid lines depict the upper and lower bounds of perceived luminance levels with the error bars indicating the standard error of mean (SEM). The blue dashed line represents the mean of the two other curves. The characters indicate the luminance of the disk L_{disk} for each glare model (see Section 3). The black dashed line at 220 cd/m^2 is the actual luminance of the disk in the reference images.*

are performed and reveal that, for all cases, the Gaussian method produces stronger perceived luminance ($t(14) = 1.71, p = .05$, $t(14) = 1.73, p = .05$, $t(14) = 1.96, p < .05$, for D, E and F).

To further investigate the relationship between perceived luminance and L_{disk}, pairwise contrasts between levels of L_{disk} are computed for both methods. To control the family-wise error rate, the p-values are adjusted, using the method proposed by Holm [1979]. The results of this analysis are illustrated in Figure 6. The indicated sets depict levels for which the perceived luminance values are statistically indistinguishable on a 95% significance level. For the Gaussian method, a "jump" in perceived luminance between the third and the fourth level arises, after which an increase in luminance does not further elevate perceived luminance. For Spencer et al.'s method, the increase occurs earlier between level B and C.

The answers of the subjects to the questionnaire presented after each trial are summarized in Table 1. For both Methods, the application of the glare models produces a "glowing" impression of the disk and is independent on how strong the glare is rendered. The results from Question 2 indicate that Method II is more likely to induce a Mach-band effect, which might be one aspect of an explanation of why Method II does not produce as strong an effect as Method I. However, another factor that probably helps to induce the difference between the Methods is the size of the disk that increases with growing L_{disk} for Method I much stronger than for Method II (see Figure 3). This fact is also highlighted by the results for Question 3 of the questionnaire.

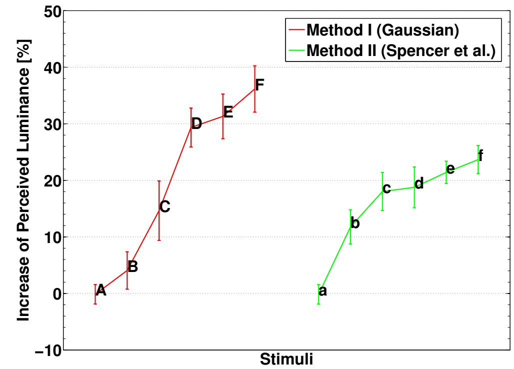
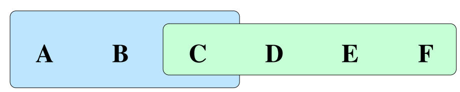
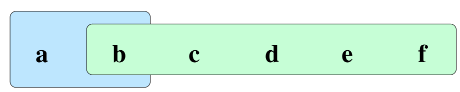


Figure 5: *The percentage of increase for the mean perceived luminance levels compared to the actual luminance of disk 220 cd/m^2 for Method I (Gaussian, red) and Method II (Spencer et al., blue). Error bars denote the standard error of mean (SEM). The characters indicate the setting of the L_{disk} parameter.*



(a) Method I (Gaussian)



(b) Method II (Spencer et al.)

Figure 6: *Similarity groups of the L_{disk} levels as revealed by post-hoc contrasts at a 95% significance level for the Gaussian method (a) and Spencer's method (b). Items in the same set were statistically indistinguishable.*

6 Discussion

In our psychophysical experiment, we employ Spencer et al.'s model [Spencer et al. 1995] and a Gaussian convolution model to produce a glare illusion. Both Methods succeed in eliciting a strong glare illusion. It is shown that an increase in the chosen parameter results in a larger amount of perceived luminance. For high values of the luminance of the disks, the Gaussian Method produces a stronger boost in perceived luminance than Spencer et al.'s method.

However, the Gaussian method results in a stronger increase of disk size when large parameter values are chosen. Therefore, the finding that Gaussian kernels produce a stronger illusion should be taken with a pinch of salt since larger areas are often perceived as brighter [Li and Gilchrist 1999]. It is therefore possible, that the apparent advantage of the Gaussian method is due to the increase of the size of the glare source rather than an advantage of the Gaussian method per se. We therefore conclude, that both Methods produce a comparable increase in perceived luminance when reasonable parameters are chosen. This is interesting also from a practical point of view,

Method I (Gaussian)						
Luminance of disks L_{disk}	A	B	C	D	E	F
Questions	220	1165	2110	3055	4000	7000
Q1: Does the reference image glow?	0	60	90	100	100	100
Q2: Do you see a bright ring (a.k.a. Mach-band)?	0	10	20	50	80	90
Q3: Are the sizes of reference and target disks the same?	90	100	30	10	0	0
Method II (Spencer et al.)						
Luminance of disks L_{disk}	a	b	c	d	e	f
Questions	220	1480	2740	4000	7000	10000
Q1: Does the reference image glow?	0	100	90	100	100	100
Q2: Do you see a bright ring (a.k.a. Mach-band)?	0	70	80	80	80	90
Q3: Are the sizes of reference and target disks the same?	90	80	30	0	0	0

Table 1: *Questionnaire. Percentages of the answer 'yes' over 10 subjects. Colors indicate either above (red) or below (blue) 50%.*

since a convolution with a separable Gaussian kernel is much faster than in case of non-separable kernels required for the eye's PSF.

Yet, there are differences in how the two Methods behave in terms of potential side-effects. While the Gaussian method is relatively susceptible to distort the shape and size of the convolved object, Spencer et al.'s method is more robust regarding the choice of the parameter and therefore less likely to produce this effect (even though it does change the disk shape with growing L_{disk}, see Figure 3). On the other hand, Spencer et al.'s method is more likely to excite a Mach-band effect, which is often perceived as objectionable. This might be caused by the steeper gradient in the glare image rendered with Spencer et al.'s method (see scanlines in Figure 3) as shown in [Ratliff 1965, pp. 85].

It is interesting to note that models of the optics in the human eye [Stiehl et al. 1983; Spencer et al. 1995] do not outperform the simple Gaussian convolution approach in terms of pure effectiveness of boosting the perceived luminance. These results allow the speculation that the glare effects (or disability glare) are not necessary related to the glare illusion (refer to Section 1). Although the smooth gradient profiles used to evoke the glare illusion are similar to the perceived illusionary glow around bright light sources, these two effects do not need to be strictly related to each other.

7 Conclusions and Future Work

If rendered properly, the glare illusion can increase the perceived luminance and therefore also the dynamic range of a display by 20–35%. Although the glare illusion is believed to be related to optical distortions in the eye, our experiment indicates that faithful simulation of the eye's optics is not necessary to achieve a strong brightness boost. The glare illusion produced by a Gaussian convolution can give the same increase of perceived luminance as a complex PSF of the eye, is less likely to cause undesirable Mach-band effects and is faster to render. On the other hand, the spiky profile of the eye's PSF does not change the object's shape and size as much as the Gaussian kernel.

In future work, we would like to measure how other factors, such as background, extend of the glare profile (σ) and the size of the object, affect perceived luminance increase due to the illusion. A model that includes all these factors would allow to render glare of desired strength and appearance.

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