HDR IN CONSIDERATION OF THE ABILITIES OF THE HUMAN VISUAL SYSTEM

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ABSTRACT

In recent years, High Dynamic Range (HDR) has been improved enormously. The capability of cameras and displays to reproduce small differences in luminance levels is constantly growing. However, we are still dealing with a limitation of the human visual system (HVS) known as the simultaneous contrast range (SCR). Compared to earlier studies, this paper focus on real-world scenarios for evaluating the SCR. In natural images bright highlights, especially in HDR, can limit the eyes' sensitivity to detect small differences in surrounding dark areas. The paper on hand describes a different test-image set - developed as part of current research activities by the authors - to measure the relation between the perceived SCR and the following four significant parameters: The distance or rather the viewing angle, the size of the bright highlight, the luminance of the highlight and the ambient light. As a result, a mathematical formula is given which can help to evaluate and improve HDR viewing experiences as well as SDR down-conversions.

INTRODUCTION

The human visual system (HVS) is a very complex model, not only dealing with the eyes but also with neuronal reception, processing, and interpretation of information. It is commonly known that this system can distinguish differences in intensity within a very wide range of luminance levels using mechanical and biochemical adaptation processes. However, the adaptation processes take time. On the contrary, the steady-state or simultaneous contrast range (SCR) of the HVS is extremely limited compared to the overall range. The range of the simultaneous visible contrast however, it not yet exactly examined.

When introducing High Dynamic Range (HDR) into the television industry, this question becomes more important. The sensitivity of cameras, as well as displays, has increased tremendously over recent years which allowing the capturing and reproduction of a contrast range several times larger than classic SDR-TV. New technologies will even further improve this capability over the coming years. This leads to new challenges for manufactures, as well as for content producers and raises different issues about viewers' preferences as described in an earlier paper [1]. With all these technological improvements the question is whether we shall reach, or have already reached, the limitations of the HVS toward the SCR.

We use the term 'contrast range' instead of 'dynamic range' in this paper, because 'dynamic' defines the quantization. This could lead to a misinterpretation (just focusing only on the number of bits for the quantization). However, when using a non-linear OETF, e.g. a logarithmic transfer curve, a relatively small dynamic range is sufficient to capture a wide contrast range. In this case, the 'contrast' is more precise.

RELATED WORK

In 2004 Seetzen et al [2] introduced a new way to construct displays by combining a panel of LEDs which can individually be controlled together with a LCD. The new age of high contrast displays had just started. For this reason, Kunkel et al [3] tried to provide guidance in display design with their 'Reassessment of the Simultaneous Dynamic Range of the Human Visual System'. They pointed out that a high discrepancy can be found in the literature, spanning from about 2 orders of magnitude to 3.5 orders of magnitude for the SCR of the HVS, which is a difference of up to 1500%. As an explanation they observed that none of the results came from a direct measurement. They were calculated from the eye's photoreceptor response curves. So, it is a problem of interpretation and a lack of clear definition. Because of the complexity of the HVS, we believe that the process of vision has to be treated as a whole. Therefore, looking at the eye's photoreceptor response curve is not enough.

Kunkel et al carried out a psychophysical study with 'Gabor gratings' showing a small luminance modulation (stimulus) on a noisy grey background. The idea is that the same relative (percentage) change in luminance will produce different response increments in the HVS. In the case where the stimulus has a similar luminance as the adaption state, the increment will be the largest and will get smaller with an increasing difference. Consequently, the luminance of the stimulus was increased and afterwards decreased as long as the response increments fell below the visual threshold. The range between these two thresholds is the SCR, and was measured to be 3.7 log units.

The authors have admitted that several parameters in the design of the experiment influence the results. They recognized that showing a stimulus which is more strongly modulated for a longer time at a higher adaption brightness, leads to a higher contrast range exceeding the number of 10000:1 (often referred to in other publications) and reaching the display limitations.

But there is another limitation. In former studies we found out that the SCR can be seriously reduced in real-world scenarios. [4] In the experiment performed by Kunkel et al the dark and the bright thresholds were successively measured. Depending on the content, a natural image deals with highlights and shadows at the same time. So, it is almost comparable with measuring the full on/off contrast instead of the simultaneous contrast. The bright parts, especially in HDR, can limit the eye's sensitivity towards slight differences in the dark surrounding areas. Similar masking effects are used in audio coding (eg. mp3) to reduce the bandwidth because quiet sounds will not be heard as long as they are close to loud sounds. Transferred to HDR we can ask the question: Why do we need so much gradation in the dark if it cannot be seen anyway under certain circumstances?

The experiment [4] showed that highlights could reduce the contrast range even below a range of 300:1. Compared to the ideal conditions this is quite a big difference. However, to get more quantitative results for different situations, the test has to be exceeded – for instance the luminance in the mentioned experiment [4] was limited to 100 cd/m^2 and the viewing angle was not varied.

Dolby [5] performed extensive tests when designing the PQ approach. They were also dealing with bright and dark areas in different test images but not simultaneously.

TEST DESIGN AND PROCEDURE

In order to get more quantitative results, we set up a new test design to evaluate and quantify the described effect, as well as our assumptions, in more depth. [6][7] The goal was to measure the sensitivity towards slight differences in dark and bright areas at the same time on a high brightness display. The tests were performed on a LCD LED 58” UHDTV with a peak luminance of about 1000 cd/m^2 at 30% of the display size. A special test image set was designed. Several iterations were required to reach the final setup. Figure 1 shows some of the iterations. In a first setup, two bars were used at the outside of the image showing gradation in black and white. The highlight was placed at the centre. It became obvious that there has never been a problem to distinguish between the brightest two patches. This could also be because of the limited luminance of the monitor used. Therefore, we focused on how glare would affect the dark parts only. Moreover, we changed the layout, moving the gradation to the centre so the observer could stay focused on the middle part of the test image. We tried to keep the distances in luminance between the patches, small and as perceptual equidistant as possible. The values are given in Table 1. Letters in absolute black were placed inside the patches to ask the test person if they could distinguish it. Instead of one highlight, two highlights were placed on both sides as can be seen later on (Figure 2).

patch no.	luminance	patch no.	luminance	patch no.	luminance
1	0.38 cd/m^2	2	0.32 cd/m^2	3	0.28 cd/m^2
4	0.25 cd/m^2	5	0.21 cd/m^2	6	0.18 cd/m^2
7	0.16 cd/m^2	8	0.14 cd/m^2	9	0.13 cd/m^2
10	0.12 cd/m^2	11	0.11 cd/m^2	12	0.10 cd/m^2
13	0.09 cd/m^2	14	0.08 cd/m^2	15	0.07 cd/m^2
16	0.06 cd/m^2				

Table 1 – an overview of the cd/m^2 values

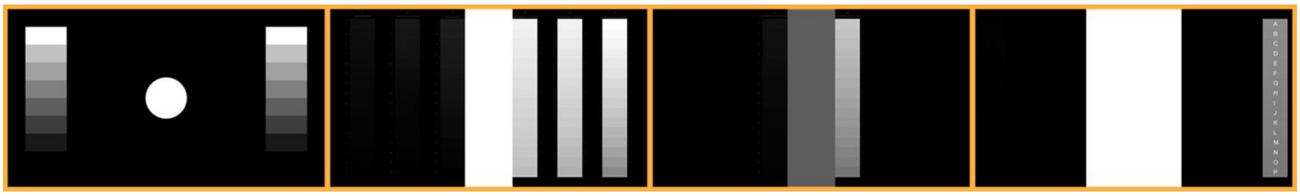


Figure 1 – some iterations of the test image (image borders marked in orange)

Afterwards, we generated 36 (3x4x3) different versions of the template varying the three degrees of freedom, namely the distance between the highlight and the dark gradation, the size of the highlight and the luminance of the highlight. An overview is given in Table 2.

In the following, the distance is given as a viewing angle (in degrees) making the parameter independent of the display size. Therefore, the field of view between the outer edges of the highlight bars was measured. For a better visual impression, all variations of the test image are shown for one luminance level in Figure 2. Please note that the luminance levels of the grey patches in Figure 2 were modified in order to be visible in the printed paper.

parameter	number of steps	unit	name of steps			
distance to highlight	3	viewing angle in °	close	medium	far	
size of highlight	4	% of the whole image	2.5	10	20	30
luminance of highlight	3	cd/m^2	1000	300	100	

Table 2 – an overview of the variation of the three different parameters

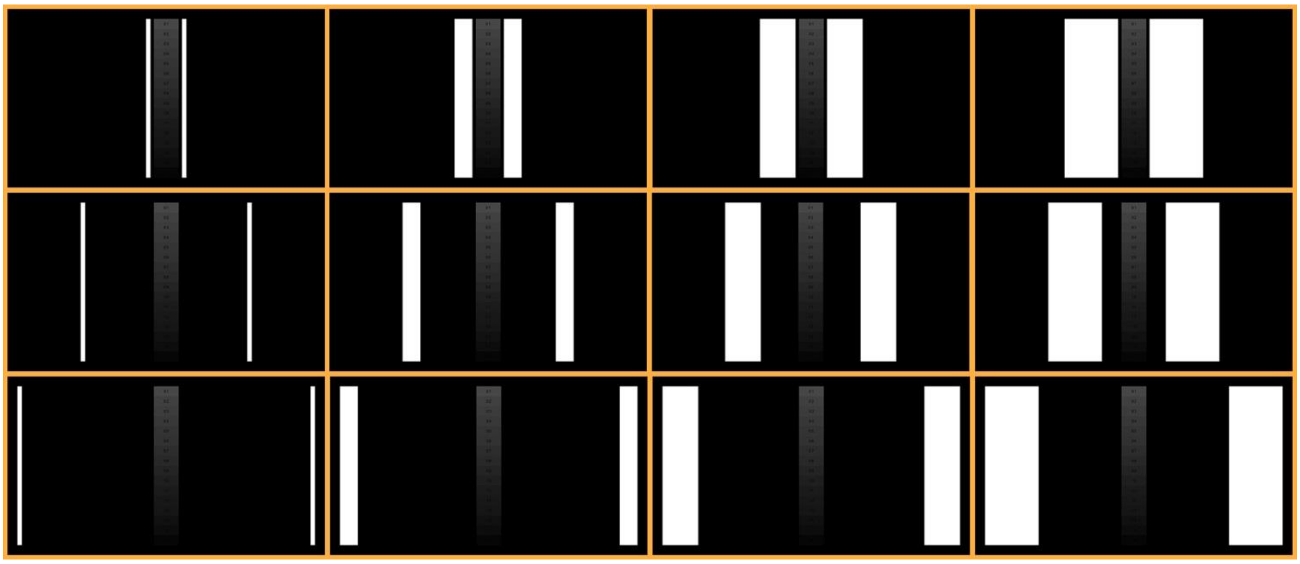


Figure 2 – all variations of test images for one luminance level

(image borders marked in orange)

The order of the letters which were placed on the patches was changed randomly. The test persons were forced to give an intuitive answer within a few seconds to avoid adaptation processes. The test was repeated under three different environmental luminance levels (10 cd/m^2, 50 cd/m^2, 100 cd/m^2). 41 people participated in the test. 66% of them were male, 34% were female. The average age was 31.

We have to acknowledge that working with a direct LED blacklight is not the ideal way to perform this test. In the case where the highlight is quite close to the dark gradation, halos can lead to a brighter representation. In the case where the highlight is at the edges of the display, it is difficult to reach the 1000 cd/m^2 on the monitor. By optimizing the test images, the effects could be reduced significantly. Moreover, the relation between the different viewing angles nearly stays constant because both effects let the SCR seem to be tentatively higher.

RESULTS

Figure 3 shows the results of our test in different forms of presentation, visualising different aspects. We will start on the top left side (Figure 3 (a)) where the viewing distance is plotted on the X-axis and the number of dark patches which can be distinguished, on the Y-axis. The colour of each curve indicates the luminance level and the marker indicates the size of the highlight. All the curves show the same tendency of a monotonic increase. According to this, it is obvious that there is a better perception for dark levels if the distance to the highlight increases. Moreover, it can be seen that this effect is more significant for higher luminance levels and that the curves do not drive into saturation.

The 95%-confidence intervals indicate that at higher patch numbers (Table 1) the results of the test persons become more inhomogeneous. It can also be observed, that with increased age, a test person cannot distinguish as many patches. However, for every participant the progression of the curve is very similar. Also, we have to consider that the luminance of the patches is scaled in a non-linear way as described above in the chapter ‘test design and procedure’.

In Figure 3 (c), the patch number is plotted against the size of the highlight. As one would expect it becomes more difficult to distinguish between different black levels while the patch size of the highlight increases. This effect is less relevant for a SDR range compared to a HDR range. For 100 cd/m^2 and a medium distance the values vary from 0.115 to 0.155 cd/m^2. For the same case at 1000 cd/m^2 the values are from 0.135 to 0.265 cd/m^2.

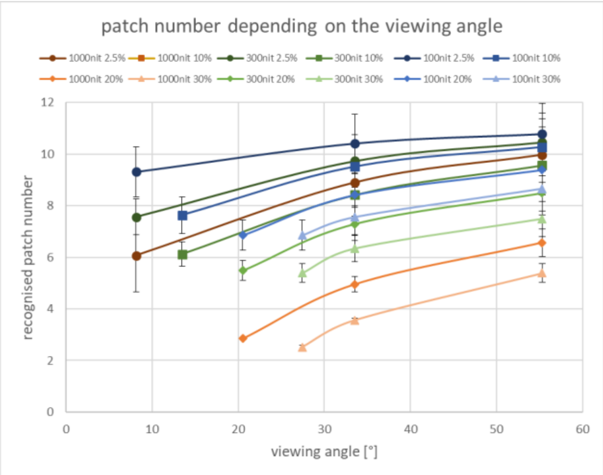
Figure 3 (e) verifies the findings in terms of the influence of the luminance of the highlight showing the luminance on the X-axis. This time the colour of the curve indicates the viewing angle. It is evident that the curves drift apart with an increasing luminance. At 100 cd/m^2 the values are between 0.11 and 0.165 cd/m^2. For 1000 cd/m^2 the values vary from 0.12 to 0.30 cd/m^2. The masking effect here is more noticeable. To summarize the results, it can be concluded, that with HDR displays, the recognized SCR is more dependent on the image content itself and in consequence highly variable.

Another interesting aspect can be observed when looking at Figure 3 (b),(d) and (f). Compared to (a),(c) and (e), the X-axis shows the contrast range on a logarithmic scale instead of the recognized patch number. Therefore, the patch number is converted to the corresponding luminance level and is calculated together with the luminance of the highlight. This time, the curves look quite different. Although bright highlights affect a test person's sensitivity towards slight differences in the dark in a negative way, they increase the sensitivity towards bright ones significantly, which results in an increasing contrast range.

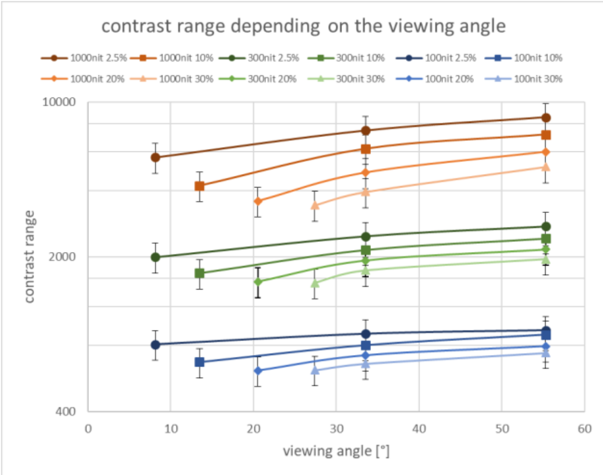
From a display perspective, it has to be realized that increasing the maximum luminance is more effective in order to reach a higher relevant contrast range than decreasing the minimum luminance.

Moreover, the effect does not drive into saturation at 1000 cd/m^2. Therefore, we assume that it is likely, that higher contrast ranges could be reached at 2000 cd/m^2 or even 4000 cd/m^2. For the best case (small highlight, far distance) at 1000 cd/m^2, a contrast range of about 8500:1 was measured in the experiment. We assume that values above 10000:1 are possible for higher luminance levels. This result corresponds pretty close to the Kunkel experiment. The 95%-confidence intervals are very constant when scaled as a contrast range (Figure 3 b,d,f) compared to the 95%-confidence intervals for the black level (Figure 3 a,c,e).

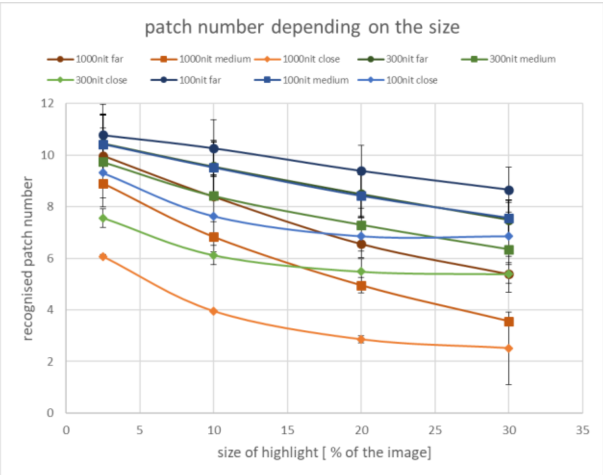
In a second step, we tried to set up an approximation formula based on the psychophysical experiment, which can estimate the SCR of the HVS. In the following Equation 1, the luminance of the highlight is referred to as L_{max}, the viewing angle as α and the size of the highlight as s. The values for the three constants k are determined by iterative tests ($k_1 = 15.7$,



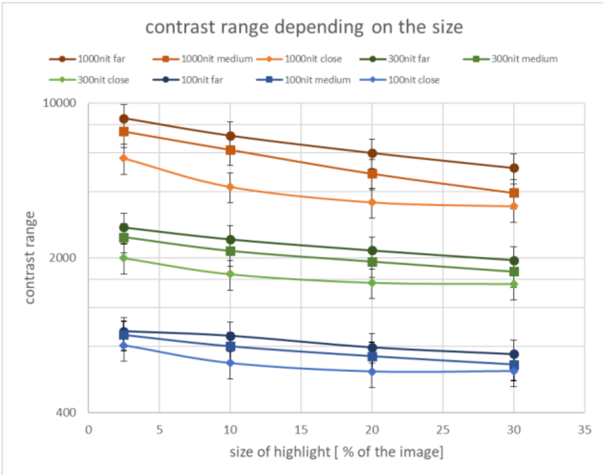
(a)



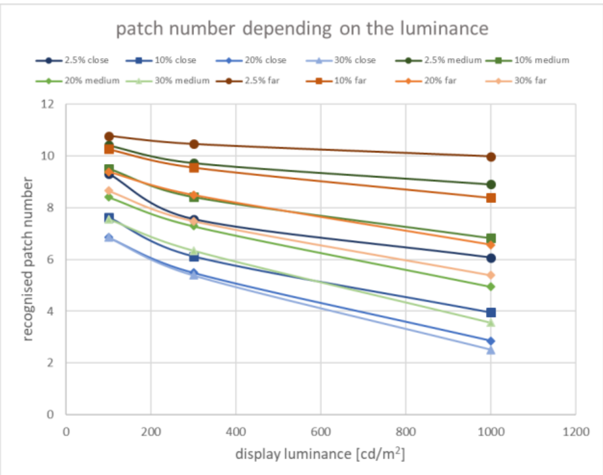
(b)



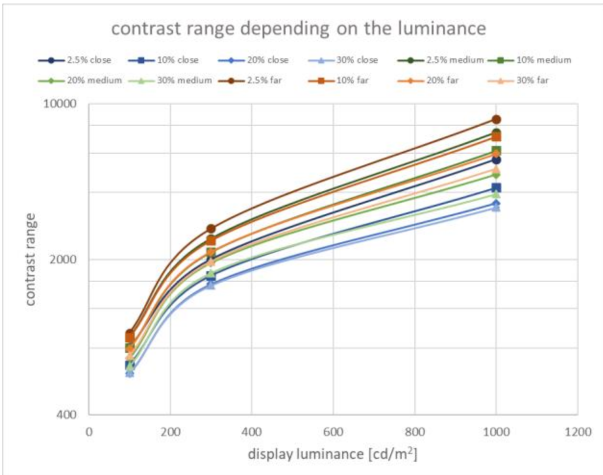
(c)



(d)



(e)



(f)

Figure 3 – The diagrams show the results from the viewer test. On the left side the recognised patch number for the different test images is shown. On the right side the visual relevant contrast range is given.

k_2 = 0.22, k_3 = 0.18). A comparison of the measured results and the formula output is given in Figure 4 for all 36 test images. It can be seen that they match very well. The mean deviation is 5.7%.

$$SCR = L_{max} * k_1 * \left(\frac{\left(\frac{\alpha}{100}\right)^{k_2}}{(1+s)^{k_3}} \right)^{log_{100}(L_{max})} \qquad \text{(Equation 1)}$$

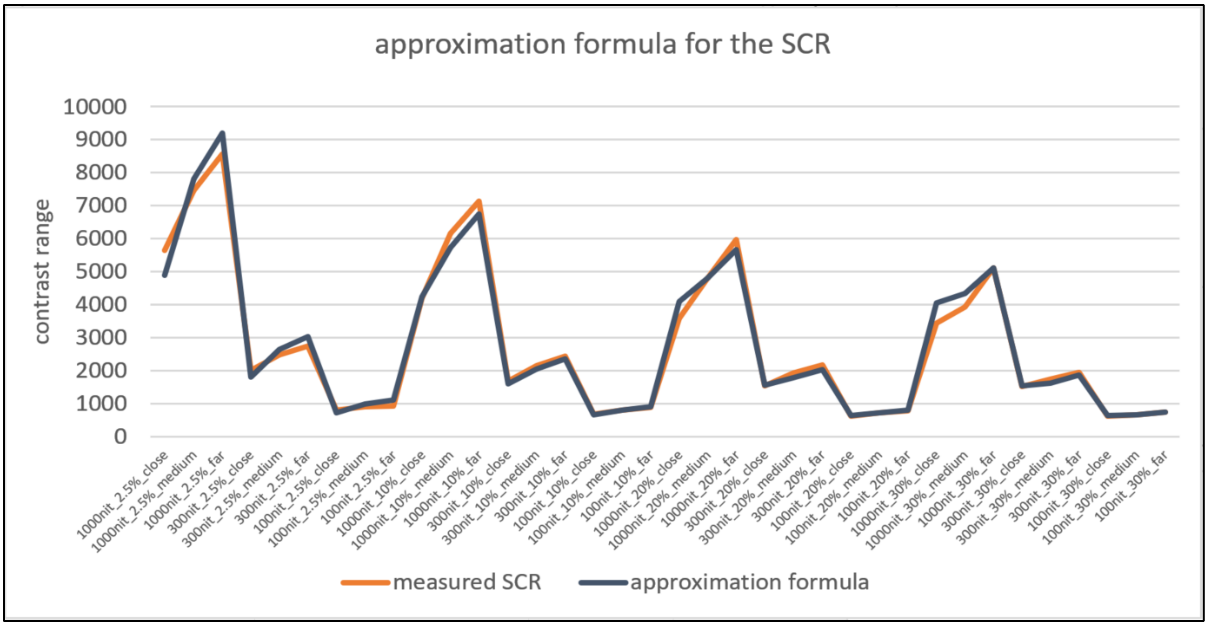


Figure 4 – Comparison of the approximation formula to the mesured results

Next we investigated the impact of environmental luminance on the SCR. As you would expect less black patches could be distinglished when repeating the experiment with a brighter ambient light. However, this effect is more remarkable on the test images where the masking effect of the highlight is relatively low.

In the first round, the experiment was performed with a ambient luminance of 10 lux. In this case the contrast range varied from 616:1 to 8561:1 depending on the test image. For 50 lux and 100 lux, the range was reduced to 570:1 to 7245:1 and 557:1 to 6534:1 respectively. This shows that in a real-world scenario two masking effects, one depending on the image content in terms of luminance distribution and the other depending on the ambient light, prevent a higher SCR being reached.

CONCLUSION AND OUTLOOK

With the conducted tests it could be shown that the simultaneous contrast range can significantly be reduced by glare. Highlights can affect the eye's sensitivity towards small differences in the shadows depending on the size of the highlight and the viewing angle. Consequently, more information will get lost when dealing with a small display. It became obvious that the masking effect correlates with the luminance of the highlight, which shows the importance for HDR compared to SDR. For the first time, not only qualitative but rather quantitative values are given, resulting in a general equation.

Therefore, we conclude that scene luminance values should not always be reproduced one-to-one on a HDR display. Non-uniform scenes could even look worse in HDR because of glare. Homogenisation techniques, such as using different windows in colour grading, could help to compensate the effect. For live scenarios, where it is not possible to change the light setting in a scene and where it is not possible to use windows for colour grading, sectional tone mapping as described in [8] could be used even for HDR in the future.

However, it could be shown that increasing the display luminance will extend the capabilities of the simultaneous contrast range. This would not be possible using SDR.

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