The luminance of pure black: exploring the effect of surround in the context of electronic displays

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ABSTRACT

The overall image quality benefits substantially from good reproduction of black tones. Modern displays feature relatively low black level, making them capable rendering good dark tones. However, it is not clear if the black level of those displays is sufficient to produce a "absolute black" color, which appears no brighter than an arbitrary dark surface. To find the luminance necessary to invoke the perception of the absolutely black color, we conduct an experiment in which we measure the highest luminance that cannot be discriminated from the lowest luminance achievable in our laboratory conditions ($0.003\,cd/m^2$). We measure these thresholds under varying luminance of surround (up to $900\,cd/m^2$), which simulates a range ambient illumination conditions. We also analyze our results in the context of actual display devices. We conclude that the black level of the LCD display with no backlight dimming is not only insufficient for producing absolute black color, but it may also appear grayish under low ambient light levels.

Keywords: Display black level, HDR display, detection thresholds, blackness induction, black limit, pure black, absolute black, real black.

1. INTRODUCTION

The quality and aesthetics of displayed images strongly depends on the overall image contrast,[1,2] which is mostly determined by an electronic display black level. Dark tones are abundant in professional photographs and theatrical movies, therefore quality of a display equipment often depends how well these tones can be reproduced. These resulted in a series of innovations leading to the displays capable of producing $10^6 : 1$ contrast ($0.0004\,cd/m^2$ black level for $400\,cd/m^2$ peak luminance). It is, however, unclear if such low black level is actually necessary, as the eye may not be able to distinguish between such low luminance levels.

To find the luminance necessary for invoking the perception of the absolutely black color, we conduct an experiment in which we measure the highest luminance that cannot be discriminated from the lowest luminance achievable in our laboratory conditions ($0.003\,cd/m^2$). Since no color can be perceived as darker than the measured luminance threshold, the threshold is a conservative estimate of the highest luminance of the perceived black.

Such lowest discriminable luminance depends on a scene content and it can be expected to be much higher for brighter scenes. To capture this dependency, we measure the thresholds in relation to two factors: surround luminance and stimulus size. Another reason for choosing these two factors is that we want to find the lowest luminance that an electronic display could benefit from. Therefore, stimulus size simulates the size of a black region and surround luminance corresponds to ambient light conditions: from dark-room to sunlight.

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1.1 Perceived, real, perfect, solid, absolute and pure black

Several notion of black could be found in literature, each representing different perception of black color. The luminance of a gray stimulus could be lowered until the stimulus appears no longer gray but black. Such level of black, however, will strongly depend on the other stimuli in the field of view. In the presence of even darker stimuli, the black pattern may no longer appear to be black. For example a black chip on a Macbeth color checker chart may actually appear grayish when compared with a black velvet patch. In this paper we are interested in the measure of *pure black* (also known as real, perfect or solid black), which is the highest luminance that could no be distinguished from the stimuli that has almost zero luminance level ($0.003\,cd/m^2$ in our experiments). Such measure is a conservative estimate of the desirable black level of a display regardless of a scene content. In this paper we also use the term *absolute black* to denote an almost zero luminance level ($0.003\,cd/m^2$), which we use as a reference to find the luminance of pure black.

1.2 Black level in display technologies

Electronic displays are never absolutely black. The increased brightness of display black level, which we understand as the luminance of the pixels set to 0, comes from three sources: ambient light reflected from a display screen; light emitted by the display, even when pixel values are set to 0; and scattered light coming from the nearby brighter pixels, which is known as a display flare.

CRT displays often look grayish even when they are powered off, especially when they are compared with LCD displays. This is because the glass screen of a CRT coated with fluorescent layer reflects more light than an LCD panel. CRT display emits certain amount of light when showing black image because of the gun amplifier's offset, which is controlled by the brightness setting of a display.

LCD display panels rely on light polarization to transmit more or less light from a backlight. Although it is possible to produce a polarizer that polarizes almost 100% of the light, its transmittance would be very low, making it impractical for a display. Therefore LCD panel design is usually a trade-off between light polarization, which reduces light transmittance for black pixels and thus improves the black level, and transmittance, which improves display brightness. Newer LCD displays try to improve black level by dimming backlight depending on the image content. If the dimming is applied evenly to the entire display and is modulated over time, it is known as a dynamic contrast. If the dimming is non-uniform on a display backlight, it is known as a 2D dimming, backlight modulation, or an HDR display.[3] The performance of the dimming depends on the backlight technology: cold cathode fluorescent lamps (CCFL) can be usually dimmed not lower then 20% of they maximum emission while LED backlight could be dimmed to almost arbitrary low levels. In practice, however, the uniform-dimmed displays became too dark if dimmed to very low levels, and spatially modulated (HDR) displays suffer from a strong flare coming from non-dimmed LEDs. Achieving low black levels in HDR displays is also a challenging problem because of artifacts that appear due to the insufficient resolution of an LED array.[4]

Plasma displays are often cited as having better black levels than LCD displays. This is because the photon emission of each sub-pixel cell is controlled by the voltage, which can be theoretically set to 0, resulting in no light emission. In practice, however, each cell on a plasma display has to be precharged before it is due to be illuminated, otherwise the cell would not respond quickly enough. This precharging means the cells cannot achieve a true black.[5]

Organic light-emitting diode (OLED) displays do not need backlight to emit light and are free from the limitations of plasma displays. Front-projection systems, such as DLP projectors are mostly affected by the ambient light reflected from a screen. Since such a screen must be white for optimum performance, the black level in projection systems strongly depends on ambient light. Black level in both front- and back-projection systems is also limited by the lens flare. Each glass-air interface in the lens system reflects from about 1% of the light for lens with anti-reflective coatings to about 4% of the light for bare glass. For the system with 5-10 lens elements, the reflected light forms a lens flare that significantly raises the black level of a project image.

This a short overview shows that achieving a very low black level in different display technologies often requires compromising display brightness, efficiency or increases display costs. Therefore, it is desirable to know what is the highest luminance, which would appear as black and would not be objectionable to a human observer. This is the major motivation for our experiment, which we describe in the next sections.

2. RELATED WORK

The effect of surround on the luminance detection thresholds was investigated in the context of disability glare. The optics in the eye is not perfect and a certain amount of light coming to the eye is scattered in the lens and on the retina, thus elevating retinal luminance. Such luminance elevation due to scattering of light coming from brighter scene objects reduces physical contrast on the retina and therefore reduces visibility. The effect is know as disability glare and has been thoroughly measured in relation to eccentricity, observer's age and iris color.[6,7] The most accurate model of the disability glare, especially for large angles and low spatial frequencies, has been published in the CIE Research Note 135.[8] However, these studies have never considered the case in which the test patch was black.

The perception of blackness was investigated in the spatial induction experiments.[9,10] In these experiments a central low-illuminated disk was shown together with the brighter surround annulus. Both were separated by a dark gap. The observers were asked to adjust luminance of the surround until the central disk turned black and its contour disappeared. The experiments demonstrated that brightness induction is related to luminance of the surround and does not involve chromatic pathways.[10] We argue that the stimuli used in these experiments did not allow to find the most conservative thresholds and thus the lowest "pure black" luminance, since the dark gap was affected by glare from the surround, thus lowering contrast between the gap and the test disk.

Recently the impression of blackness under varying surround luminance was studied by Eda et al.[11] The participants were asked to rate the blackness level using word descriptions from deep black to bright gray, for a test disk surrounded by a uniform field of varying luminance. Their result indicate that the contrast 100:1 between the test patch and the surround is sufficient to invoke the perception of deep black. The reported contrast seems to be very low, especially that our result indicate that people can still see darker tones at the contrast higher than 1000:1. We attribute this low contrast result of Eda et al. to a particular design of their experiment: the test patch was relatively small (1.5 deg), no reference of the lowest possible luminance was presented next to the test patch, and the scaling method used in their experiment was less conservative than much stricter two-alternative-choice procedure used in our experiment.

Rempel at al. measured preference for a display black level and brightness in short video clips.[12] They found that all participants consistently set the black level to the lowest possible settings, which was about $0.3\,cd/m^2$ for the display used in their study. Although the same display technology is used in our study, we achieve much lower black levels with the help of neutral density filters.

3. EXPERIMENTAL METHODS

3.1 Stimuli

The stimuli was shown on the 37" high dynamic range (HDR) LCD display capable of modulating both its LED backlight and the front LCD layer (HDR37 from BrightSide Technologies / Dolby Canada). The display was chosen because of its very high peak brightness ($1000\,cd/m^2$ for uniform field, $3000\,cd/m^2$ for isolated spots), and contrast (up to 30000:1). Figure 1 shows a stimulus, which consists of a square that is divided into two halves shown on a uniform surround. One half-square had always the lowest achievable luminance while the other had the target luminance. Both halves were randomly swapped for each trial.

Running an experiment with the stimuli from Figure 1 leads to two problems. Firstly, even an HDR display cannot produce very low luminance levels (due to the internal display flare) and it cannot be precisely controlled in its lower luminance range. Secondly, very low luminance levels are difficult to measure with sufficient precision. We solved both of these problems by covering the square with a neutral density (ND) filter (Kodak Wratten gelatin filter 2.0 D $150{\times}150\,mm$) and rendering the area underneath the filter at higher luminance. The reference square was $0.0032\,cd/m^2$ for the darkest surround ($0.098\,cd/m^2$) and 0.1484 for the brightest surround ($900\,cd/m^2$). Such low luminance levels are usually not possible with a projection or display setup because of the light scattering in the projector optics (glare) or in a display (flare).

The prototype display used in this experiment was very difficult to calibrate because its response was affected by the power and heat management circuits. To avoid error due to unreliable calibration, we measured the luminance of the background and the halves of the square for the stimuli corresponding to the detection threshold

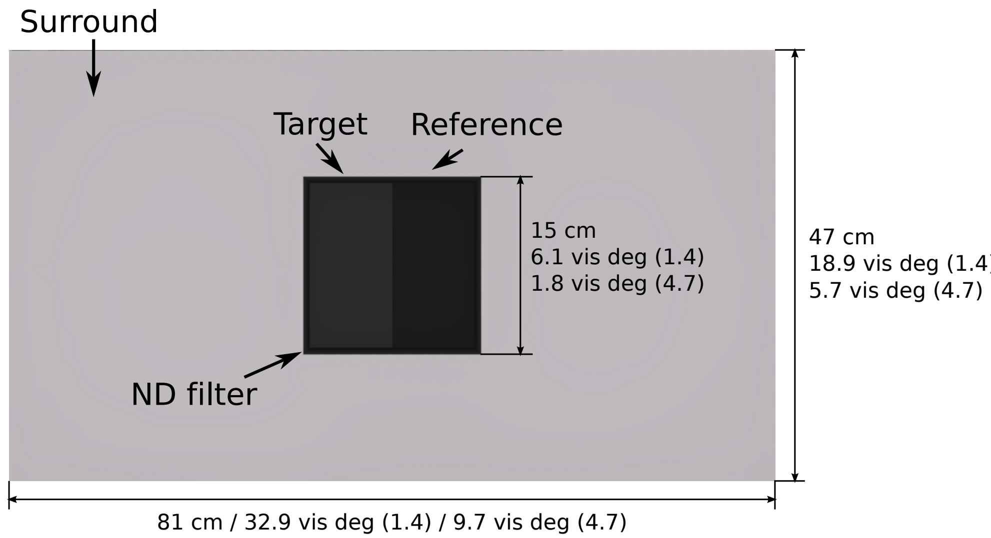

Figure 1. Stimulus used in the experiment. The task was to determine which part of the square in the middle is brighter. The numbers in parenthesis denote the viewing distance (in meters) for which angular size is given.

after each experiment. The luminance of the halves was measured using the Minolta luminance meter LS-100 after removing the ND filter. The measurement was then compensated for the ND filter transmittance (measured with the same luminance meter: 0.0139).

The stimuli was shown at 2 viewing distances: $1.4\,m$ and $4.7\,m$, which corresponded to the square size of 6.1 and 1.8 visual degrees. A chin rest was used for the closer viewing distance to ensure that the distance did not change during the experiment. The vertical size of the surround for the two distances was 18.9 and 5.7 visual degrees. In the pilot study we experimented with additional viewing distances, but we found that the effect of distance is too small to justify more measurement points. Closer distances also pose problems because of the light reflected from the chin rest and participant's face.

3.2 Subjects

Four participants took part in the experiment, all with near perfect or corrected vision. All but one participant (the first author) were naive about the purpose of the experiment. The participant RKM made three repetition of each measurement to assess intra-subject variance. The other participants made single measurement for closer viewing distance and two measurements for further distance to compensate for the higher variance. The age of the participants ranged from 28 to 33 years.

3.3 Experimental procedure

The participants were asked to select the brighter part of a square or if they could not see any difference, they were asked to guess. The PEST procedure[13] with a 75% target probability was used to select luminance levels for the trials. There was no time limit for a trial. To achieve better dark-adaptation state, each participant waited 5 minutes in a dark room before starting the experiment and the stimuli were shown from the darkest to the brightest background. Although 5 minutes are not sufficient to achieve complete black adaptation, such condition better corresponds to a typical display viewing scenario, in which the eye is never completely dark-adapted.

Our task was different from most measurements of the detection thresholds, in which participants are instructed to choose the time interval in which a stimulus can be seen. This is because the goal of our study was finding the highest luminance that does not look brighter than the reference absolute black, rather than testing for detection thresholds. Such two interval measurements would also test for edge detection rather than for brightness difference.

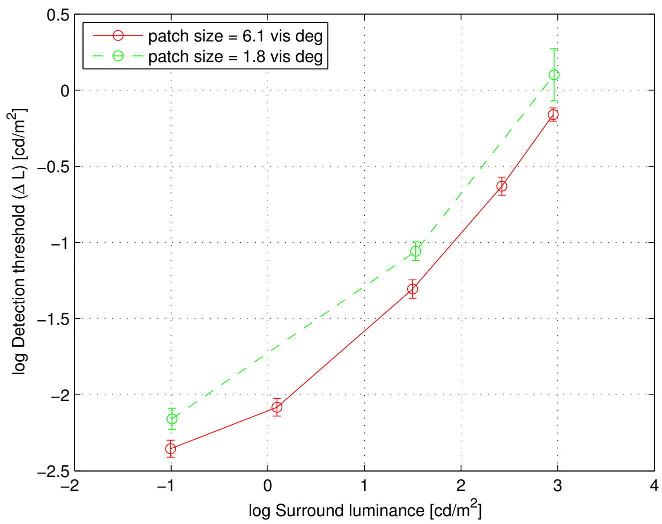

Figure 2. Experimental results: detection thresholds as the function of surround luminance and patch size.

The visibility thresholds could be also tested with more rigorous stimuli, such as Gabor patches, which are known to evoke the highest sensory response. That would, however, introduce another unknown variable, which is spatial frequency, and would test for pattern visibility rather than for appearance.

4. RESULTS

Figure 2 shows measured detection thresholds averaged over all participants. The thresholds are given as increment thresholds ($\Delta L = L - L_{black}$) rather than increment contrast values ($\Delta L/L_b$) because of the very low luminance of the reference absolute black L_b (darker half of the square), which could not be measured reliably due to the display flare. The intra-observer variance for subject RKM was 13.8% (11.1% for the 6.1 vis. deg stimuli and 18.2% for the 1.8 stimuli). The inter-observer variance was 18.4%.

The detection thresholds shown in Figure 2 increase with the surround luminance and with decreasing stimulus size. Both effects are expected because brighter surrounds produce more light scattering in the eye and smaller stimuli are more affected by the glare. The thresholds could be potentially even smaller if the reference patch was even darker than $0.0032\, cd/m^2$, which we used in the experiments. We decided to use the reference at that luminance level because we did not observe much change in the threshold when stronger ND filters were used.

In Figure 3 we plot the results as a log-10 contrast between surround luminance and the measured luminance of the absolute black. The contrast varies from 3.1 log-10 units for the brightest surround and the larger patch to 1.2 log-10 units for the darkest surround and the smaller patch. Although modern displays can produce such contrast (some LCD panels offer contrast 3000:1), in the next section we demonstrate that most display will not achieve the luminance of pure black in a typical viewing conditions.

5. REALISTIC DISPLAY SCENARIO

Our measurement procedure assumed a perfect display, which could achieve extremely low black-level (the lowest luminance), regardless of the ambient illumination. This was because the experiment was performed in a totally dark room and an ND filter was used to further reduce displayed luminance. In reality no display can achieve so low black-level because of display internal reflections (display flare) and the light reflected from its screen. Even the anti-reflecting coating usually cannot reduce light reflections below 1-2% for a broadband light, so that the influence of the ambient illumination cannot be avoided.

We simulate the scenario, in which a display is positioned in an uniformly illuminated room in front of a white diffuse wall (reflectance 90%) and the screen is perfectly diffuse. To find the correspondence with our

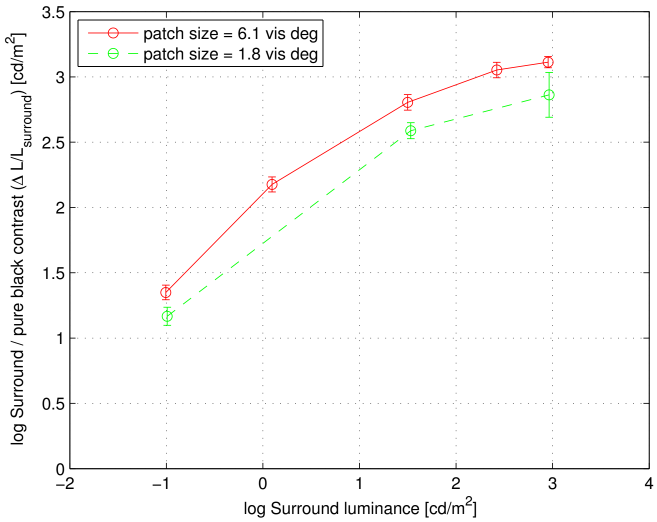

Figure 3. log-10 contrast between surround luminance and pure black.

measurement, we convert luminance ($L_{surround}$) to illuminance (integral over a hemisphere) given the surround reflectance R_{white} (90%):

$$E_{ambient} = \frac{\pi \, L_{surround}}{R_{white}} \tag{1}$$

where $E_{ambient}$ is the ambient illumination in lux. The black level of the display, L_{bl}, with screen reflections can be modelled as:

$$L_{bl} = R_{disp} \, \frac{E_{ambient}}{\pi} + L_{min} \tag{2}$$

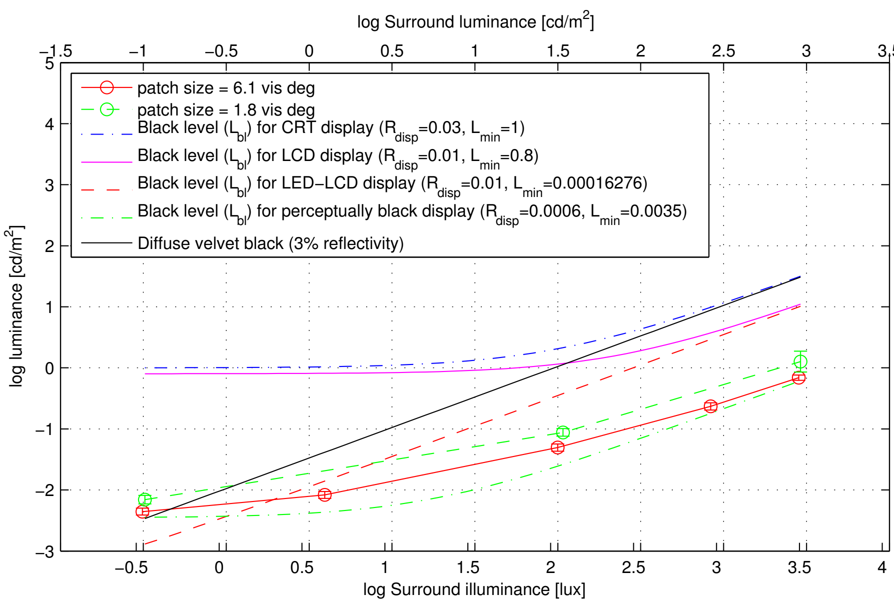

Figure 4. Detection thresholds compared with the black level of four displays and a black diffuse surface. The top axis represents luminance of the surround in cd/m^2 while the bottom axis represents the corresponding ambient illumination in lux.

where R_{disp} is the reflectance of the display screen and L_{min} is the minimum luminance produced by the display (black level without screen reflections). In Figure 4 we plot the data from Figure 2 in relation to the ambient illumination $E_{ambient}$. The results are plotted as absolute luminance levels ($L_{black} + \Delta L$) rather than increment thresholds (ΔL). We additionally include the black level for three simulated displays: a conventional CCFL-backlight LCD ($R_{disp} = 1\%$, $L_{min} = 0.8\,cd/m^2$), a CRT ($R_{disp} = 3\%$, $L_{min} = 1\,cd/m^2$) and a modern LED-LCD with spatially uniform back-light dimming ($R_{disp} = 1\%$, $L_{min} = 0.000163\,cd/m^2$). The parameters were selected to correspond to actual displays we measured. Because the black level of the LED-LCD display was below the lowest value that LS-100 could measure, we estimated it as: peak luminance ($450\,cd/m^2$ $\times$ LCD panel contrast (1/2700) $\times$ LED contrast for 10-bit digital to analog converter (2^{-10}). The curves for all displays ignore an internal flare due to bright pixels in other screen regions. Such a flare could be significant, especially for a spatially modulated backlight (HDR displays). The black continuous line on the plot shows the luminance reflected from a black diffuse surface (reflectance = 3%), such as black velvet.

We can make several interesting observations based on the plot in Figure 4. Only the LED-LCD display offers the black level that is equal or lower than the pure black level found in our experiment, and only for very low ambient light ($< 0.3\,lux$). Despite potentially very high contrast offered by modern displays, the black level is heavily elevated by the light reflected from a screen as well as relatively high minimum light emission. When compared with velvet black (3% reflectivity), the CRT display appears grayish for ambient light below $300\,lux$, and the LCD display appears grayish below $100\,lux$. This is because the display effective black level is higher than the luminance of a diffuse black surface. The LED-LCD display with backlight dimming will always appear darker than diffuse black. However, a perceivable improvement is still possible for higher ambient light levels as that the eye can distinguish between 3% diffuse black and even deeper black, for example that of a lacquered black surface.

We also found the parameters of a hypothetical "perceptually black display" (see dash-dotted green curve in Figure 4) with a black level below "pure black" curves. Such a perceptually conservative display would need to emit not more than $0.0035\,cd/m^2$ for black pixels and its screen would need to reflect less than 0.06% of light. This means that LED-LCD displays are in fact darker than necessary, but this is assuming no flare. The black level below "pure-black" can help to offset the effect of display flare. Although there are displays emitting very low light, finding a material that reflects no more than 0.06% of light is unlikely. The best low-reflectance nickelphosphorous black coatings reflect as much as 0.4% of light and only for selected wavelengths.[14] However, in practice a display screen reflectivity around 1% is unlikely to be objectionable since there are not many objects in real-world that would have lower reflectivity and thus appear darker than a display. Moreover, if the reference pure black is missing in the scene, the thresholds for luminance of black colors can be expected to be much higher than in our measurements.

The slope of the pure black curves is lower than 1, indicating a loss of contrast sensitivity. As a consequence of this the difference between diffuse black (reflectance 3%) and even deeper black becomes less distinguishable at very low ambient light levels. This is shown as the crossing of the solid black line (diffuse surface) and "pure black" lines in Figure 4. The pure black curves constitute the lower limit of luminance perception, indicating a point where even large contrast becomes invisible because of insufficient number of photons reaching the retina.

6. CONCLUSIONS

Our results show that the luminance perceived as a pure black is as low as $0.0044\,cd/m^2$ for surround luminance equal $0.1\,cd/m^2$ but raises to about $1\,cd/m^2$ if the surround is $900\,cd/m^2$. The black level improvement in the LED-LCD displays with backlight dimming is appreciable for two reasons: Firstly, the black level in conventional displays with no backlight dimming is brighter than diffuse black already below $100\,lux$, making them appear grayish in dimly illuminated rooms. Secondly, the experimental results indicate that the eye can appreciate even deeper black than "diffuse black", which motivates the need for further reduction in display black level. The LED-LCD displays with backlight dimming can potentially achieve black levels below the pure black, but only for a pitch dark viewing conditions. Light reflections from the screen are major limitation of the display black level, even in dimly illuminated rooms. Our considerations also do not account for the display flare, which strongly elevates black levels as soon as any image content is shown.

In the future work we would like to find a visual model that would explain the pure black threshold we found in our experiments. Our initial work on the visual model indicates that the visual difference predictor for high dynamic range images (HDR-VDP)[15] can predict these thresholds if used with the glare model from CIE report.[6] Such a visual model could determine an actual luminance limit for the perceived black color that depends on the scene content. This would let us estimate the luminance of pure black in a more complex display scenario, in which both display black level as well as perceived black are elevated by the displayed content.

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