New Contrast Metric for Realistic Display Performance Measure

Alex D. Hwang, Eli Peli
Schepens Eye Research Institute, Massachusetts Eye and Ear, Department of Ophthalmology, Harvard Medical School, Boston, MA

Abstract
The contrast ratio (CR) has been used to describe display's performance. However, CR is unbound, ignores the impact of ambient illumination, or viewer's contrast perception. We propose new metric for display's contrast performance based on a modified Weber contrast definition that considers human contrast adaptation and applies for both opaque and see-through displays.

Keywords
Contrast metrics; Weber contrast; Contrast ratio

1. Objective and Background
The contrast ratio (CR) has been used by the display industry as a metric of display performance for presenting visible luminance or brightness differences. However, this metric largely misrepresents the performances of the display under varying ambient luminance conditions, because 1) it only depends on minimum and maximum luminance pixel values, e.g. pixel values of 0 and 255, as measured in total darkness, 2) does not incorporate the impact of ambient illumination, and 3) lacks consideration of viewer's contrast perception, which varies based on viewer's luminance adaptation.

We are presenting a new contrast metric based on perceptually appropriate modified Weber contrast (WC) definition that handles varying ambient light conditions. It also represents the visibility of luminance differences among all possible combinations of pixel values while considering luminance adaptation of human vision system.

Kelley et al. [1] and Penczek et al. [2, 3] presented a model of viewing scenario for see-through and opaque displays, assuming a single ambient light source. In their model, reflected light and transmitted light were computed based on reflectance and transmittance of the display, then they were linear superposed to the display generated onscreen light to estimate the real-world contrast performance of device based on the CR.

We present a modified display viewing model (Fig. 1), where each light component (L_{Target}, $L_{Background}$, $L_{Reflected}$, and $L_{Transmitted}$) on a display can be easily measured independently. $L_{Background}$ and L_{Target} can be measured under completely dark ambient condition, and $L_{Reflected}$ and $L_{Transmitted}$ can be measured under given lighting conditions with the display turned off. This model applies equally well to see-through and opaque display, covering desktop and mobile opaque displays, as well as see-through HMD/HUD.

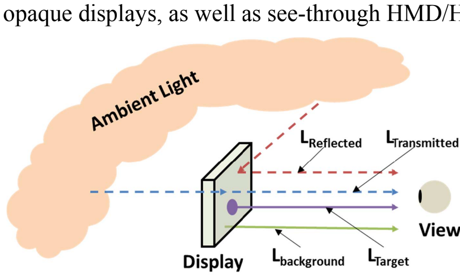

Figure 1. A model of light components that reach viewer's eye under any ambient light conditions

With this model, the luminance of each pixel is composed of the sum of the display emitted luminance (measured in the dark) and the luminance due to the ambient light, as expressed in Eq. 1, which is measured with the display off under given light condition. The visibility of a target (of a single pixel value) can be expressed as contrast ratio (Eq. 2 & 3), or Weber contrast (Eq. 4 & 5), which considers the contributions of ambient light components. Note that the target can be either brighter than background (*positive polarity*), or darker than the background (*negative polarity*).

The novel modified Weber contrast definition [4], which is compatible with both positive and negative polarity contrast conditions, was used to compute the Weber contrast including the effect of the ambient light. When the display is non-see through type, $L_{Transmitted}$ becomes zero. In this case, only the $L_{Reflected}$ remains as the ambient light effect.

$$L_{Ambient} = L_{Reflected} + L_{Transmitted} \tag{1}$$

$$CR_{Positive} = \frac{(L_{Target}+L_{Ambient})}{(L_{Background}+L_{Ambient})} \tag{2}$$

$$CR_{Negative} = \frac{(L_{Background}+L_{Ambient})}{(L_{Target}+L_{Ambient})} \tag{3}$$

$$WC_{Positive} = \frac{(L_{Target}-L_{Ambient})-(L_{Background}+L_{Ambient})}{(L_{Target}+L_{Ambient})} = \frac{(L_{Target}-L_{Background})}{(L_{Target}+L_{Ambient})} \tag{4}$$

$$WC_{Negative} = \frac{(L_{Background}+L_{Ambient})-(L_{Target}+L_{Ambient})}{(L_{Background}+L_{Ambient})} = \frac{(L_{Background}-L_{Target})}{(L_{Background}+L_{Ambient})} \tag{5}$$

Note that the reflected or transmitted lights are superposed (added) on both target and background luminance, but unlike the contrast ratio, the effect of those ambient light components only affects the denominator portion of the Webber contrast function, representing observer's visual adaptation to the ambient light level.

2. Results
We computed contrasts of uniform luminance targets (e.g. letters) over a uniform background on hypothetical displays that can present pixels of luminance range from 0.1cd/m^2 to 500cd/m^2, placed under various ambient light conditions, which results in uniform ambient luminance (1cd/m^2-10,000cd/m^2) directly projected to the viewer. Under the sampling sphere configuration described in [2], this ambient luminance range covers display viewing conditions of from dark nighttime or indoor darkroom to daylight outdoor conditions.

 ISSN 0097-966X/16/4702-0982-$1.00

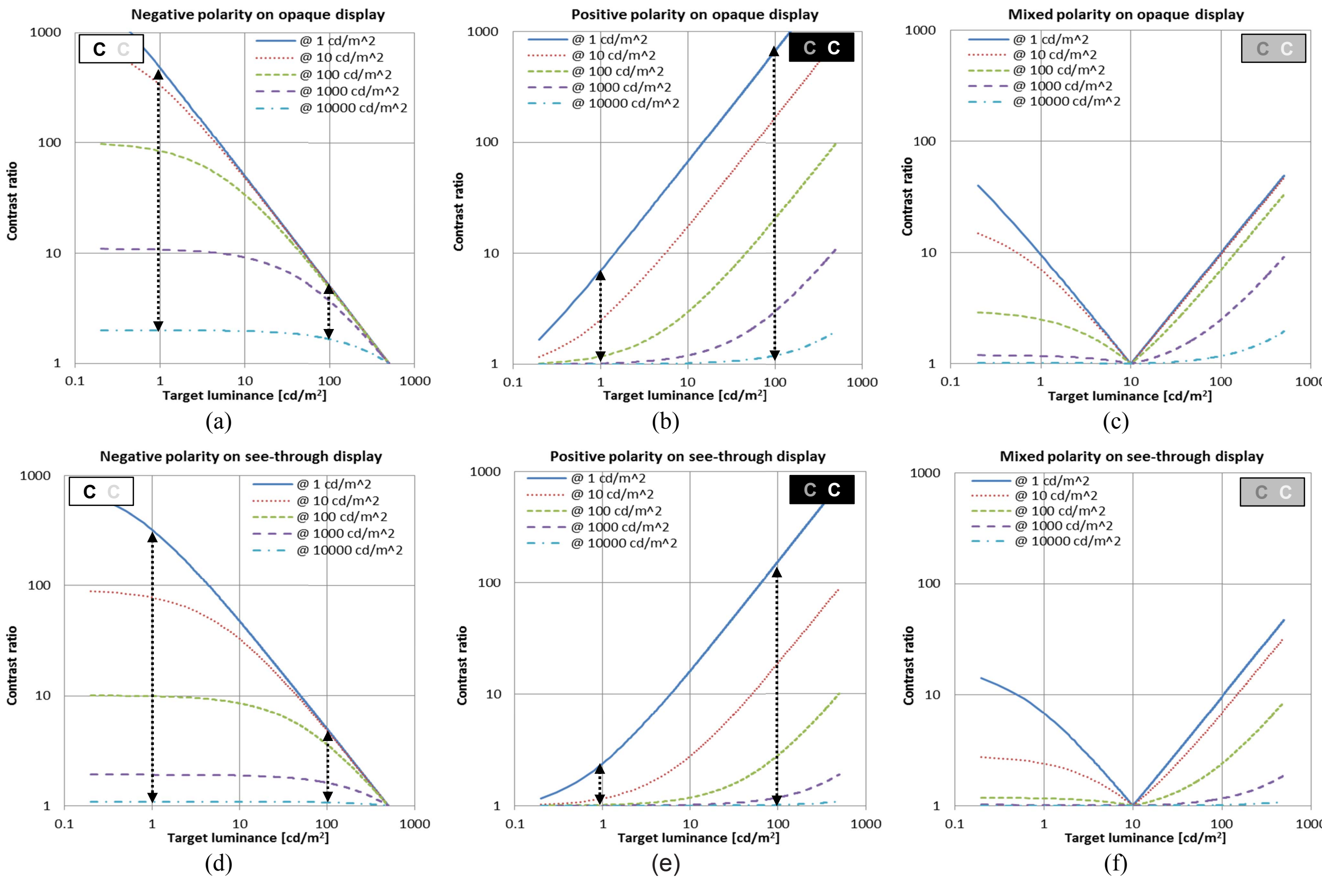

Figure 2. Contrast ratio (CR) changes of (a-c) opaque display, and (d-f) see-through display under varying ambient illumination conditions, which results in uniform ambient luminance of 1cd/m^2 to 10,000cd/m^2. Emitted screen background luminance is assumed to be maximum (500cd/m^2) in (a, d), minimum (0.1cd/m^2) in (b, e), and about a half on the log scale (10cd/m^2) in (c, f), while the target (pixel) luminance varies over the available range. The representative image content for the positive, negative, and mixed polarity contrast conditions are illustrated in the inset. The impact of the ambient light on low and high luminance targets are indicated as the arrows representing the changes in CRs in maximal ambient light variation.

In the example shown above, the calculations assumed, without any significant effect on the generality of the results, that the reflected luminance ($L_{Reflected}$) is 5% of the ambient luminance, and the transmitted luminance ($L_{Transmitted}$) is 50% for see-through display condition, and 0% for opaque display condition. These values are consistent with the range of transmittance and reflectance of the LCD and OLED displays measured in [3].

Fig. 2 illustrates changes of contrast ratio (CR) of opaque (a-c) and see-through displays (d-f) under various ambient luminance conditions (as shown in the insets legends) for displaying negative (a & d), positive (b & d), and mixed polarity stimulus (c & f).

For each contrast polarity, the onscreen emitted background luminance ($L_{Background}$) is assumed to be 500cd/m^2 (pixel value=255), 0.1cd/m^2 (pixel value=0), and 10cd/m^2 (in between), while the target luminance is varying over the available luminance range (pixel value 1-254).

With these configurations, for given maximum or minimum luminance background, as the target luminance increases (in negative polarity contrast condition) or decreases (in positive contrast polarity condition) such that they approach to the background luminance level, the contrast ratio decreases to its minimum value of 1, as expected.

Also, in all plots of Fig. 2, it can be observed that the contrast ratio of given luminance targets are reduced as ambient luminance increases (as shown in black dotted arrows in Fig. 2a & b). However, for both negative (Fig. 2a & d) and positive (Fig. 2b & e) contrast polarity conditions, the effect of ambient light, which is a reduction of contrast ratio due to ambient light conditions change, is larger at the high contrast ratio target range (0.1cd/m^2-10cd/m^2) than low contrast ratio target range (10cd/m^2-500cd/m^2), as it can be compared within each plot.

If we consider the contrast ratio as a measure of letter visibility, and a display is displaying both high and low contrast letters of the same contrast polarity, Fig. 2 suggests that when the display viewed indoor is moved outdoors under bright sunlight condition, the visibility reduction of the high contrast letter is much larger than the low contrast letter, and at certain ambient luminance condition, the visibility of the high contrast letter reduces to the visibility of the low contrast letter then both will become invisible at the same time, which is clearly not the case. In real world, higher (negative) contrast content is quite resilient to the impact of the ambient light, while the low contrasts contents are more vulnerable to the ambient light condition changes.

Another thing to note for Fig. 2 is that the patterns of contrast ratio change under the same changes in ambient luminance condition are different for the two contrast polarity cases. The curves illustrating the contrast ratio changes in negative (Fig. 2a & d) and positive (Fig. 2b & e) polarity contrast conditions are 'concave transition to 1:1 line', and ‘convex transition to 1:1 line’, respectively. The mixed contrast polarity condition (Fig. 2c & f) better illustrates this CR difference with respect to the two target polarities. This is despite evidence that the contrast perception of positive and negative polarity is almost symmetrical [5, 6].

The contrast ratio based visibility predictions fail because it does not consider the function of the observer’s visual system. Human vision achieves high dynamic range through luminance (retinal) adaptation. As the overall scene luminance increases or decreases, the viewer’s adaptation level normalizes the target to background luminance difference, and perceives the same contrast (*contrast constancy)* [7, 8]. For example, a large absolute luminance difference displayed under high overall luminance condition is perceived to have the same contrast as a lower absolute luminance difference displayed under low overall luminance condition. This characteristic is embedded in the Weber contrast definition.

The Weber contrast definition, widely used in vision and clinical science, incorporates the element of perceptual luminance adaptation at its definition. It thus automatically corrects many limitations of the contrast ratio based target visibility measure. Fig. 3 shows the plots of the same hypothetical display under the same ambient luminance conditions as in Fig. 2, but the contrast values are calculated using our modified Weber definition [4].

The Weber contrast of target decreases rapidly to zero (0), as the target luminance approaches near to the background luminance level, while it converges slowly to contrast of 1.0 as the target luminance depart from the background luminance level at all ambient light conditions. Note that those lines in the positive polarity contrast plots (Fig. 3b & e) do not seem to converge to zero because of lack of luminance resolution in low pixel values.

Fig. 3 shows that the impact of ambient light variation is much stronger for positive polarity (Fig. 3b & e) than negative polarity contrast condition (Fig. 3a & d). The interaction between the ambient light and target brightness is distinctively stronger in positive polarity contrast condition than negative contrast condition, where the contrast in low target contrast range (lower target luminance range in positive contrast condition) is more strongly affected by the presence of ambient light than the contrast in high target contrast range. Note that the amounts of contrast change due to the ambient light in negative contrast case (Fig. 3a & d) are maintained constant at relatively minimal level, for wide target contrast range.

This indicates that if the content to be displayed is composed of negative polarity (e.g. greyscale letters on white background), and viewed in dim indoor light then gradually moved to brighter outdoor ambient light, only the lowest contrast range contents will lose its visibility, while the rest of contrast range contents will maintain relatively stable visibility. However, if the content is composed of positive polarity contrasts (e.g. greyscale letters on black background), the visibility reduction will gradually happen from the lowest contrast range contents to the higher contrast

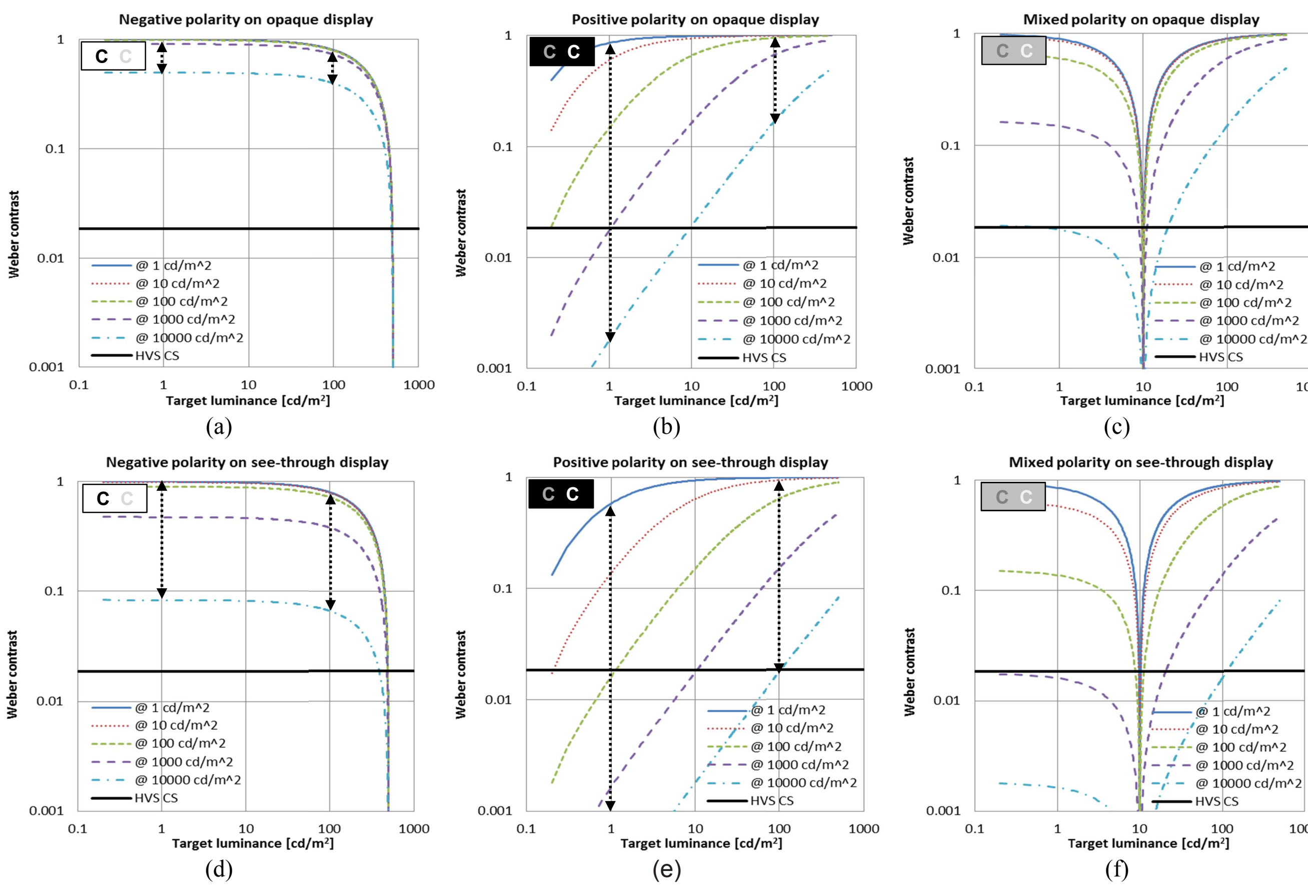

Figure 3. Weber contrast (WC) changes of opaque display (a-c), and see-through display (d-f) under varying ambient lighting conditions. Background luminance is assumed to be maximum (500cd/m^2) in (a, d), minimum (0.1cd/m^2) in (b, e), and about a half in log scale (10cd/m^2) in (c, f), while the target luminance varies over the available range. The horizontal black line represents the contrast threshold of normal vision observer, log (1/WC) = 1.8. Note that no such reference is possible in Fig 2.

range contents. As a result, only the higher (positive) contrast will be remained visible at the end of the transition because the rest of the lower contrast contents fall below viewer's contrast threshold.

Note that since the normal vision human's contrast sensitivity ($1/WC_{Threshold}$), which is the lowest contrast threshold that a subject can see, is between 1.73 and 1.99 in log scale [9], the corresponding contrast threshold can be drawn on the plots (marked in Fig. 3 as black horizontal line). Any target with contrast (including the impact of ambient light) below the threshold line will not be visible to the viewer.

Fig. 3 also indicates that more dramatic contrast reduction will happened with see-through display (Fig. 3a & b) than opaque displays (Fig. 3a & b) in bright ambient conditions. For example, wider range of positive contrast contents on opaque display (Fig. 3d) will be maintained its visibility throughout the ambient light transition than the same contrast contents on see-through display (Fig. 3e).

In addition, if we consider an image composed of both contrast polarities letters (Fig. 3c & f), it is expected that even for letters of the same contrast, those negative polarity letters disappear first (becomes lower than contrast threshold), as ambient light increases. These results on the mixed polarity are particularly important as it suggests an effective way to compensate for the ambient light. With increase ambient light, what we want to do is reducing the mean luminance and stretching the dynamic range of higher pixel values (corresponding to higher pixel luminance range), and compress the dynamic range of the lower pixel values (corresponding to lower luminance values). Although it might be somewhat unintuitive, such change will maintain more of distinct contrast pixel values above threshold, which is more crucial for viewers.

Although the Fig. 3 shows the Weber contrast responses to target brightness changes for each condition as continuous lines, in modern display technology, the target luminance is usually quantized to 8bit pixel values for multiple color channels (e.g. red, green, blue, and alpha). Therefore, the contrast plots for a digital display will be limited to 256 distinct target brightness levels, and the range of visible pixels can be decided by computing each pixel value's Weber contrast and applying human vision's contrast threshold, which is also measured in Weber contrast definition.

3. Discussion

Based on the observations of the Weber contrast responses to the target luminance differences, and normal human vision's contrast threshold (as shown in Fig. 3), we can now define a display's realistic contrast displaying performance by assuming that the stimulus to be shown on the display covers all the combination of pixel value levels (range from 0 to 255).

For given ambient light conditions (e.g. dark, indoor, and outdoor), the contrast performance of display can be computed in terms of how many pixel value combinations are visible to a viewer, as follows: 1) Measure the luminance of each pixel value and ambient luminance as explained above. 2) Compute the Weber contrast for each pixel value with respect to a background level. 3) Compute the number of pixel values that survives after applying the human contrast threshold. 4) Repeat the process 2) - 3) for all possible background pixel values (0-255). Finally, compute the average ratio of survived number of pixel values over all background conditions.

This metric measures the dynamic range of visible contrasts that a display can generate under varying viewing conditions. Note that this matric depends not only on a display's ability to generate a brightest or darkest pixel, but also on the display specific mapping of pixel value to luminance range (Gamma function [10]).

4. Impact

The new metric based on the (modified) Weber contrast definition and normal vision viewer's contrast sensitivity leads to more realistic performance measure of a display in real-world viewing conditions where the ambient light level changes substantially.

With the resent increase of interests on mobile and wearable devices, and HMD / HUD, this metric provides a perceptually relevant tool to measure the general display performance over varying viewing conditions so that those display devices can be optimized for viewer.

For example, this metric can be implemented as a basic logic for adjusting auto brightness control of a mobile display (either see-through or opaque display) that needs to optimize battery usage while keeping the best available contrast visibility for various viewing conditions, or used as a tool for designing new gamma functions for particular viewing condition, such that the display's limited dynamic range is fully utilized.

5. Acknowledgements

Supported in part by NIH Grants R01EY024075.

6. References

[1] E. F. Kelley, M. Lindfors, J. Penczek, "Display daylight ambient contrast measurement methods and daylight readability", Journal of the Society for Information Display, 14(11), 1019-1030 (2006).

[2] J. Penczek, E. F. Kelley, P. A. Boynton, "Optical Measuring Methods for Transparent Displays", In SID Symposium Digest of Technical Papers, 46(1), 731-734 (2015).

[3] J. Penczek, E. F. Kelley, P. A. Boynton. "General Metrology Framework for Determining the Ambient Optical Performance of Flat Panel Displays", In SID Symposium Digest of Technical Papers, 46(1), 727-730 (2015).

[4] A.D. Hwang, J. Jung, E. Peli, "Contrast and contrast sensitivity measures for positive and negative polarity targets", in preparation.

[5] G.E. Legge, D. Kersten. "Light and dark bars; contrast discrimination". *Vision Research*, *23*(5), 473-483 (1983).

[6] D. A. Burkhardt, J. Gottesman, D. Kersten, G. E. Legge, "Symmetry and constancy in the perception of negative and positive luminance contrast". *JOSA A*, *1*(3), 309-316 (1984).

[7] E. Peli. "Suprathreshold contrast perception across differences in mean luminance: effects of stimulus size, dichoptic presentation, and length of adaptation". JOSA A, 12(5), 817-823 (1995).

[8] E. Peli, J. Yang, R. Goldstein, A. Reeves. "Effect of luminance on suprathreshold contrast perception". JOSA A, 8(8), 1352-1359 (1991).

[9] M. Mantyjarvi, T. Laitinen, "Normal values for the Pelli-Robson contrast sensitivity test", Journal of Cataract & Refractive Surgery, 27(2), 261-266 (2001).

[10] E. Peli. "Display nonlinearity in digital image processing for visual communications". *Optical Engineering*, *31*(11), 2374-2382 (1992).