Paper: A Model to Predict Effect of Inactive Areas on Display Contrast and Brightness

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Abstract

Many electronic displays have inactive areas that result from associated display electronics and nonimaging elements. This paper investigates how inactive area properties influence display brightness and contrast. The independent variables studied were: display resolution, width, and luminance of inactive areas, and foreground/background luminance of individual pixel elements in the active area. Stimuli included both visible and nonvisible grid structures. A luminance-matching task quantified the impact of these factors. Contrary to previously published results, a simple area-based luminance integration model describes the experimental data regardless of the visibility of the inactive area.

Introduction

The market for electronic reflective displays is on the rise. Applications such as lightweight displays for promotional advertisement, information displays such as message boards, and electronic retail signage are a few items targeted by electronic display manufacturers. It is extremely important to understand the parameters that drive display quality in order to successfully engineer systems that meet the needs of all these markets.

Technologies that fulfill the market requirements are those that have the ability to be electronically driven to update their content. In a complete system, electronics are needed to facilitate the update. These electronics cause the presence of inactive areas or gaps that delineate display pixels. The gaps vary in width, color, and luminance, causing an effect on the perceptual variables of display brightness, contrast, and color.

The active area of the pixel is defined as the area available to display information. A schematic of a pixel is shown in Figure 1. Note that the active area is smaller than the total pixel area. The inactive area is usually used to mask elements of the display that are not available for viewing (e.g., electronics, materials, etc.)

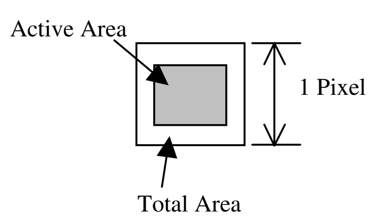


***Figure 1**. Pixel schematic*

The ratio between the active area and the total pixel area is often referred to as the display fill factor. Fill factor is an extremely important variable that drives the quality of reflective displays, which rely on ambient light for visibility. Without an increasingly powerful backlight, as in emissive displays, it is impossible to overcome low fill factors under normal viewing conditions, which result in displays with low luminance light state. It is important to understand how the display aperture relates to display quality, which is often measured by its brightness and contrast.

This research explores the processing characteristics of the human perception of contrast and lightness as it relates to the characteristics of the display inactive area. The study focuses on the display fill factor, gap luminance, and foreground/background luminance of individual pixel elements. A matching task quantifies the impact of such factors on the perceived display contrast. A scientific model that can be used as an engineering tool to maximize the design of the inactive area is validated.

Prior Art

Researchers who aim to understand the ergonomic requirements of flat panel displays have studied the characteristics of display gaps and their impact on image quality. Psychophysical studies have been conducted to evaluate the impact of the inactive areas and resulting local luminance variations on perceived quality of emissive displays[1]. Research findings state that images without inactive areas were preferred over images that have inactive areas regardless of the color of the inactive area. This is consistent with the theory that displays with high fill factors or with nonvisible pixelization are perceived as higher resolution, higher quality, and are in most cases preferred over systems that have visible gaps. Additional findings state that the integrity of the foreground is more important than the integrity of the background. Therefore, when designing information display systems, it is recommended to engineer inactive areas with the foreground color to optimize the text rendition and to avoid the visibility of the pixelization.

The presence of inactive areas has been found to significantly impact the perceived contrast of the display. Studies have been conducted to explore the perception and measurement of contrast on emissive display systems[2]. An effective luminance modulation metric is proposed by Spenkelink et al. to compute the contrast of emissive flat panel displays that have gaps. Equation (1) shows the proposed metric.

$$M_e = \frac{L_{ib} - L_f}{L_b + L_f + (2/a)\,(L_a + (1\text{-}a)\,L_g)} = \frac{L_{ib} - L_{if}}{L_{ib} + L_{if}} \qquad (1)$$

where:
- L_{ib}: integrated background luminance
- L_{if}: integrated foreground luminance
- L_f: foreground luminance
- L_b: background luminance
- L_a: luminance of reflected ambient light
- L_g: luminance of the gap
- a: portion of active area of the display

It is observed that the calculation of M_e takes into account the luminance of the gap, the portion of active area of the display, and the reflected ambient light that is a result of the viewing environment in which the emissive display is evaluated. In addition, the integrated background luminance is required for the calculation, which could be obtained by "measuring with an ordinary luminance spot meter a large enough area in the respective colours" [2]. Researchers report that psychophysical tests showed that perceived contrast is better described by M_e than by a simple contrast modulation calculation.

As previously stated, prior art suggests that the integrated luminance of the light and dark states is obtained by measuring large enough test patches that contain active and inactive areas. This can only be done for existing display panels that are tested or benchmarked. In the case where the technology is at a design stage and an actual device does not exist, a measurement of the integrated luminance is impossible. Nevertheless, there is a need to specify the optical characteristics of the components present in the display assembly including inactive areas. An understanding of the main factors that affect the integrated luminance is required prior to setting optical performance specifications. In addition, prior art focused on emissive display technology where the inactive areas were present but not visible to the observer. It is not clear if the integrated luminance model applies when the observer is at a distance were the gap is visible. This study focuses on visible pixelization and its impact on integrated luminance factor for reflective display technologies.

Research Objective

The research hereby presented explores three key aspects of display quality:

- Impact of visibility of inactive areas on perceived luminance of foreground and background areas.
- Effect of percent of active area and luminance of inactive area on integrated luminance.
- Design considerations for significant factors of display front-of-surface performance.

It is expected that a simple area-based model would describe the integrated luminance of both states regardless of the polarity of the image and the visibility of the grid. This simple model will be used to calculate the integrated foreground and background luminance, which allows for the estimation of effective luminance contrast modulation, Me, a direct correlate with perceived contrast, and display quality as demonstrated by the prior art.

The simple area-based model takes the following mathematical form:

$$Y_{if} = ff^*Y_f + (1-ff)^*Y_g \qquad (2)$$

where:
Y_{if} = Integrated luminance factor of foreground
Y_f = Luminance factor of individual foreground pixel
ff = Fill factor, percent active area
Y_g = Luminance factor of inactive area

Similarly, for the background:

$$Y_{ib} = ff^*Y_b + (1-ff)^*Y_g \qquad (3)$$

where:
Y_{ib} = Integrated luminance factor of background
Y_b = Luminance factor of individual background pixel

The above quantities are factored in the calculation of integrated luminance contrast modulation as follows:

$$iCM = \frac{Y_{ilight} - Y_{idark}}{Y_{ilight} + Y_{idark}} \qquad (4)$$

where:
iCM = Integrated Contrast Modulation
Y_{ilight} = Y_{ib} or Y_{if}, depending on image polarity
Y_{idark} = Y_{ib} or Y_{if}, depending on image polarity

Hypothesis

The hypothesis for this study states that the integrated luminance factor can be calculated as the area-weighted summation of individual pixel luminance factor and grid luminance factor regardless of grid visibility. The perceived contrast of a display device can be estimated using the integrated luminance factor of the foreground and integrated luminance factor of the background. Perceived contrast is a direct correlate of display quality.

Experimental Approach

A designed experiment was conducted to screen the variables and examine the validity of the model. Table 1 shows the experimental variables along with the range of values used for each variable.

Table 1: Experimental Parameters and Levels

Variables	Range of Values		
	Low	Medium	High
Individual Light Pixel Lightness (L*)	50	60	70
Contrast Modulation	0.60	0.70	0.80
Resolution	34	51	102
Lightness of Inactive Area	L^*_{dark}	½*(L^*_{light} + L^*_{dark}) + L^*_{dark}	1.2*(L^*_{light})
Width of Inactive Area	1 pixel	2 pixels	
Image Polarity	Positive (Light Foreground, Dark Background)	Negative (Dark Foreground, Light Background)	

The experiment was designed in terms of CIE lightness (L*) because this is a perceptually uniform quantity. The CIE relationship between lightness (L*) and luminance factor (Y) was used to calculate the corresponding luminance factor for each lightness level. The contrast modulation values are starting levels that do not account for the effect of the gaps. These values represent systems that have 100% fill factor and are used to set the luminance factor of the dark state as a function of light state luminance factor. There is a significant interest in exploring the requirements for low-resolution devices because they have a potentially low manufacturing cost. Therefore, the focus of the study was directed towards low-resolution displays. The resolution increments used in the experiment is a function of the display device used for the simulations. In addition, the lightness of the inactive area was varied as a function of the dark and light state lightness. The width of the gap area as well as the image polarity were used as block variables for the experiment.

A central composite design was used to explore the effects of the variables on the key response: integrated luminance factor of foreground and background areas. The total number of runs required by the central composite design was 26 per block variable (number of runs = 2^4 + 2 center points + 8 axial points). Some resolution-gap widths were not possible because of the resolution limitations of the simulation hardware. Therefore, the number of runs was 43 per image polarity. Because the interactions between the variables are not expected to be higher than two-way interactions, a central composite design is an appropriate choice for this study.

The test image used represents retail signage with simple text rendered at three resolution levels. Figure 2 shows an example of the test images. Note the two polarities used as block variables in the study.

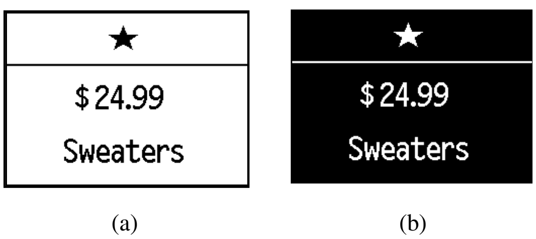


Figure 2. *Subset of images used in the psychophysical test. (a) negative polarity (b) positive polarity*

Experimental Setup

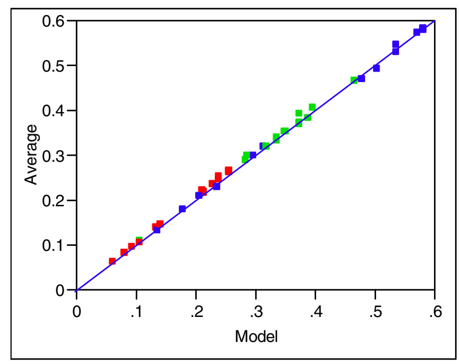
The experimental stimuli were presented on a Viewsonic LCD Monitor (Model VP2290b) calibrated to a D50 illuminant white point, set to ~190 cd/m^2. The room lights in front of the display were off, however, the gray wall behind the monitor was illuminated. The luminance from both the back wall and the monitor desktop was set to ~38 cd/m^2, roughly 20% of the monitor white point luminance. The monitor is 3840 pixels × 2400 lines, with a display area of 18.8" × 11.7", resulting in a monitor resolution of 204 dpi. This monitor enables simulated images of devices with resolutions equal to integral factors of 204 dpi (102, 68, 51, 34, etc.). Presentation of the stimuli was controlled by custom MATLAB® code that utilized the Psychophysics Toolbox http://psychtoolbox.org/). Low-level functions for real-time image processing, display, and user input were used during the implementation.

Test Methodology and Task

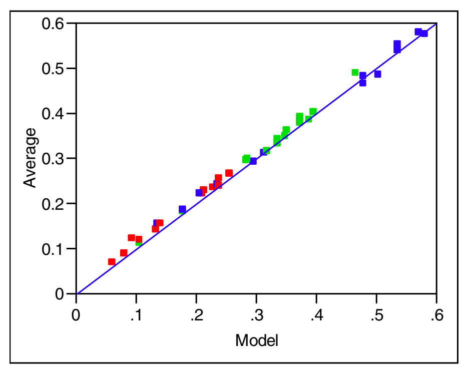
The stimuli were presented as paired comparisons. For each test stimulus (images with visible gaps), another stimulus containing nonvisible inactive areas was shown. Subjects were asked to match the foreground and background luminance of the image without gaps to that of the image with visible gaps by moving the mouse in right-left and up-down directions. Each subject was instructed to integrate the presence of the gaps and to press the left key on the mouse when a match had been reached. At that point, the RGB code values for the foreground and background were recorded and the next image pair was presented. The operations were repeated until all images, as specified by the central composite design, had been presented. The psychophysical test was divided into two sessions to address each polarity. Half of the subjects started with the negative polarity and the other half started with the positive polarity. All subjects were screened for visual acuity prior the start of the test.

Experimental Results and Analysis

A combination of experts and nonexperts participated in the study for a total of 25 judges. The average response across judges for each image pair was used to assess the goodness of fit of the area-weighted model. Using equations (2) and (3), integrated luminance values were calculated for the foreground and background of all stimuli used in the study.



(a)



(b)

Figure 3*. Integrated luminance for light state (a) background area, negative polarity (b) foreground area, positive polarity*

Figure 3a relates to the integrated background luminance (light state) for images with negative polarity. The average response across all judges on an image-per-image basis for the integrated luminance factor of the light state is plotted against predicted values for each image calculated using equation (3). As shown in the plot, the model predictions are highly correlated to the average responses obtained in the study. A similar plot is shown in Figure 3b for the integrated foreground luminance (light state) of images that have positive polarity. Equation (2) was used to predict the integrated luminance factor of the foreground area, which in this polarity is the light state area of the image. Once again, a high correlation is found between the average response of the psychophysical study and the area-weighted model predictions.

A similar analysis is made for dark regions of the image. Figure 4a shows the correlation between the model predictions and the average integrated luminance factor for the negative polarity (foreground area, Y-dark). Although the correlation is still high, there are some images for which the model predicts a higher luminance factor than the average of the responses. A similar observation is made for the model-average correlation of the positive polarity (Figure 4b). Again; in some cases the average integrated luminance factor is lower than the model predictions. In these cases the judges adjust the dark state to a lower luminance factor than what the model predicts.

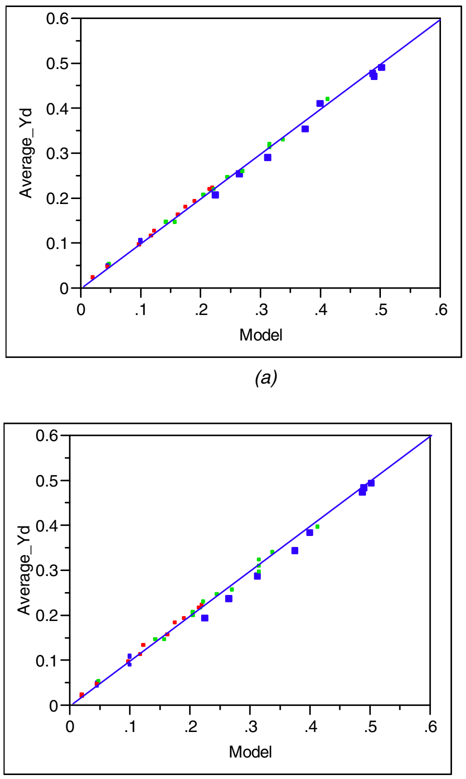


***Figure 4**. Integrated luminance for dark state (a) background area, negative polarity (b) foreground area, positive polarity*

An error analysis of the integrated luminance factor for the dark state revealed that the largest deviations between the model and the average responses were found on those images where the individual pixel luminance factor of the light state AND luminance factor of the inactive area are set to their highest experimental levels. Several experiments were conducted to understand the significance and root-cause of the deviations between the model and the average integrated dark state luminance factor. Although the deviations were visually detectable, the magnitude of the perceptual difference was found to be within experimental noise. Judge-to-judge variability and monitor achromatic nonuniformities are some of the experimental factors contributing to experimental noise.

The validation of the area-weighted model for the calculation of both the foreground and background integrated luminance factors allows design teams to estimate front-of-surface performance. The model can also be used to assess the perceptual impact of fill factor, to set luminance factor aims for individual pixel elements for dark and light states, and to evaluate the impact of the grid luminance on the overall front-of-surface characteristics. The results of the model allow for the calculation of integrated contrast modulation (see equation 4), which has been cited by prior art as the measure of display quality for information display applications.

A hypothetical example illustrates how the model can be used to determine design specifications. For this example, an individual light pixel luminance factor is assumed to be equal to 0.40. The dark pixel luminance factor is assumed to be 0.05. The aim contrast modulation for this example is assumed to be 0.70. A series of grid luminance factors and fill factors were assumed to illustrate the relationships. The area-weighted model was used to calculate the integrated foreground and background luminance factor as a function of fill factor and grid luminance. As shown in Figure 5, there are several ways to achieve the aim contrast modulation of 0.70. The design team might choose to maximize the fill factor (ff = 0.96) with a grid luminance of 0.38, or to optimize the grid luminance factor (Yg = 0.05) to compensate for lower fill factors (ff = 0.68). The decision depends on the intended application.

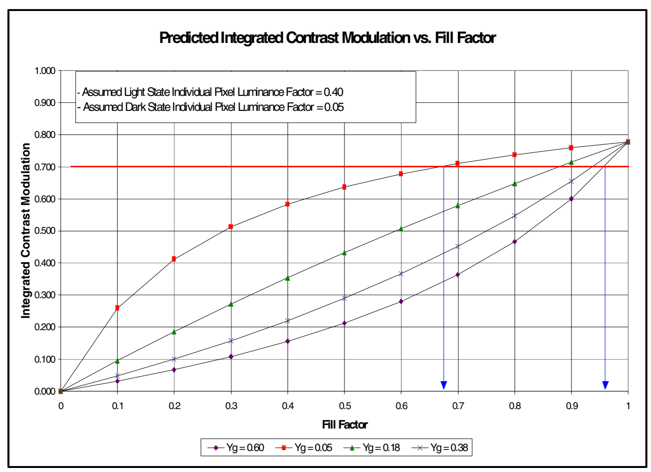


***Figure 5**. Integrated contrast modulation as a function of fill factor and luminance of the inactive area*

Conclusions

A model to predict the impact of the visibility of inactive areas on display luminance has been validated. The area-based model is a simple linear model that takes into account the fill factor, the luminance factor for the individual pixels, and the luminance factor of the inactive area. Design teams that make decisions regarding front-of-surface specifications for pixelated reflective displays can use this model to approximate the perceptual impact of fill factor, grid luminance factor, and to set aims for the dark and light states of the individual pixel elements.

The psychophysical study provides the basis for some key observations:

1. An integrated luminance model applies for visible and nonvisible inactive areas. Visible grids were the focus of this study where the area integration of luminance response was validated.
2. Integrated luminance responses can be modeled by simple area-weighted linear functions regardless of image polarity.

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Author Biography

Esther Betancourt received a B.S. in Chemical Engineering from the University of Puerto Rico and is an alumnus of the Image Science Career Development Program (ISCD) at Eastman Kodak Company. She has been with Kodak since 1992 in the role of imaging systems engineer for several product development teams including Entertainment Imaging and Consumer Digital Output. Currently, Esther supports the Display Science & Technology Research Center in the capacity of Senior Research Scientist. She focuses her research in the areas of systems analysis, computer simulations, modeling, and image quality.