Correcting the adjacent pixel nonlinearity on video monitors

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ABSTRACT

In raster-scan CRT display systems, the luminous flux of a given pixel is affected by the preceding pixel along the raster direction. This spatial or adjacent pixel nonlinearity can adversely affect image quality. High contrast, high spatial frequency regions of an image will have wrong luminances. A simple lookup table (standard gamma correction) can not correct this nonlinearity. We measured the spatial nonlinearity under a variety of luminance conditions in two CRT displays. A model proposed by Mulligan and Stone[1] was used in a 5 parameter nonlinear regression to fit the data. Results show that the model fit our data very well. We employed a two-dimensional lookup table to compensate for the spatial nonlinearity. The new lookup table has two entries: the intended luminance of the current pixel and the actual voltage of the previous pixel. The output of the new lookup table is the adjusted voltage which compensates for the pixel interaction and gives the correct average luminance for that pixel. Psychophysical experiments show that at small pixel sizes (less than 0.8 min), the compensation results in a sharp accurate image.

1. INTRODUCTION

To display an image on a cathode ray tube (CRT) raster-scan system, the image is quantized and represented as a matrix of n-bit intensities (typically n=8). These intensities are addresses of a lookup table (LUT) for gamma correction. The values in the LUT are then sequentially output to a digital-to-analog converter (DAC), and then input to the video amplifier which generates video voltages to control the electron gun. The purpose of the LUT is to correct the well known nonlinearity between the DAC output and the final luminance on the screen (so called standard gamma correction). However, there is another nonlinearity that can not be corrected by a simple LUT: the spatial or adjacent pixel nonlinearity. The luminance of adjacent pixels along the raster do not sum linearly. In other words, the luminous flux of a given pixel is affected by the preceding pixel along the raster direction[1,2,3]. The effect of this adjacent pixel nonlinearity can be seen by comparing black-white alternating pixels. When the alternation is in the raster direction, the average luminance can be dramatically lower than when it alternates perpendicular to the raster direction. It is important to consider this nonlinearity for demanding applications because it can adversely affect image quality. High contrast, high spatial frequency regions of an image will have wrong luminances.

Naiman and Makous measured the luminance profile of individual pixels using a two-dimensional CCD camera[2]. They found that the luminance of a pixel depends on the luminance of two preceding pixels and that the average luminance is not the average of individual pixels. Mulligan and Stone postulated a model for this spatial pixel interaction[1]. The model consists of an exponential low-pass filter followed by the monitor's standard instantaneous gamma function. The time constant of the low pass filter corresponds to the temporal bandwidth of the video amplifier because of the raster scan process. They measured the space-average monitor luminance as a function of pixel contrast at a constant halftone density of 0.5 and the data show a large luminance deviation from the ideal at high pixel contrast. An important motivation for the present study was the small discrepancy between Mulligan and Stone's model and their data. Also, their measurements were limited to only two adjacent pixels with 5 levels. We expand the measurements to a wide variety of luminance jumps and use a non-linear regression with 5 parameters which provides us with a better fit to the data. With the parameters from the nonlinear regression, we created a two-dimensional LUT to compensate for the adjacent pixel nonlinearity, resulting in a better displayed image.

2. METHODS

A 14" and a 19" color monitor were measured in the experiment. These two CRT displays were chosen merely out of convenience and we suspect that the spatial nonlinearity we measured for these monitors would appear in all CRT displays.

Before describing the experiments, we need to define some key terms used in this paper. Fig. 1 illustrates the process of presenting an image on a CRT display and the terms associated with each stage. We start with the luminance (L) of a given pixel in an image measured in cd/m^2. This luminance is the intended luminance ($L_{intended}$). The intended luminance is rescaled and quantized to an 8-bit intensity for most displays and it is the address (A) of a LUT (see Eqs. 4-6). This rescaled, quantized luminance will be called intensity in our experiment. Each address has a corresponding value in the LUT. This value will be called voltage (V). Rather than using units of volts we use the 0 to 255 range that is input to the DAC. The voltage is the output of the video amplifier which controls the electron gun to produce a luminance (proportional to the beam current) on the screen. This luminance is the actual luminance that can be measured on the screen (L_{actual}). There are three transformations in the process: Quantization, LUT and the gamma nonlinearity. Quantization is the process of converting the analog luminance signal to a digital signal. The LUT can be a linear ramp (no gamma correction) or an inverse function of the gamma which correct the gamma nonlinearity. The gamma nonlinearity is an accelerating function to be described by Eq. 2.

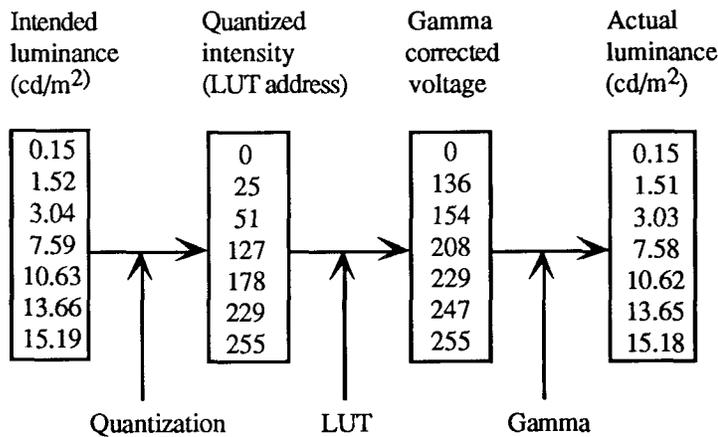| Intended luminance (cd/m^2)	Quantized intensity (LUT address)	Gamma corrected voltage	Actual luminance (cd/m^2)
0.15	0	0	0.15
1.52	25	136	1.51
3.04	51	154	3.03
7.59	127	208	7.58
10.63	178	229	10.62
13.66	229	247	13.65
15.19	255	255	15.18

Quantization   LUT   Gamma

Figure. 1. Illustration of the processes in displaying images on CRT display.

In the experiments, a test image is specified by a matrix of 8-bit intensities. These intensities are also the voltages because a linear LUT was used in our experiments (we did not correct the gamma nonlinearities in the displays during the experiments). The space averaged red gun luminance for two monitors was measured. The test area consists of 4 pixel test lines that repeat along the raster direction. Each pixel in the test pattern had one of the 8 different intensities (voltages) ranging from zero to 255. The 8 levels used in the experiment were 0, 25, 51, 76, 102 127, 191 and 255.

The test pattern consists of various luminance transitions. Four types of test patterns were used in the experiment: 1) One-level (uniform): the voltages of the 4 pixels in the repeated test pattern are set to be the same, so it is the measurement of the standard gamma nonlinearity of the monitor (8 measurements). 2) Two-levels: voltages of pixels in the test pattern were alternated between two of the 8 levels. All of the 28 possible pair-wise combinations were used. 3) Three-levels: Six test patterns of this type were used. They are listed here as voltages of the four pixels: 0-102-127-0, 0-127-191-0, 0 191-255-191-0, plus the three mirror image patterns. 4) Four-levels: each of the four pixels in the test pattern has a different voltage. They are listed in Table 3. For each of this type of test pattern, measurements were made twice: once in ascending order (eg: ABCD) and once in descending order (DCBA). Eight measurements were made on these test patterns. All together, 50 measurements were made for these four types of test patterns. Fig. 2 illustrates one of the type 2 test patterns with alternating voltages of 25 and 255.

Because of the raster scan process, it also represents the voltage output of the video amplifier as the function of time. Fig. 3 shows the output luminance profile after the gamma nonlinearity.

The 50 measurements were repeated at different contrast and brightness knob settings. These settings are listed in Tables 1 and 2. For the 14" monitor, only one knob setting was used where the contrast knob was set to maximum and the brightness knob was set to the highest level without brightening a blank (dark) screen. For the 19" monitor, the measurements were made at four different contrast and brightness knob settings so that we can see how our model parameters will be affected by these settings. In Table 1, the first column shows various knob settings. The model was applied to each set of 50 measurements made at each knob settings. In order to test the reliability of our measurements, data collections were repeated on two different days when the contrast knob was at maximum and the brightness was at minimum (Table 2). One different set of high voltages (0, 51, 102, 153, 178, 204, 229, and 255) was also used under the same condition (third row in Table 2) in order to see whether the low voltage values in our original test patterns affect our modelling results.

The luminances were measured using a United Detector Technology model 61 photometer with a precision of 10^{-2} cd/m^2 at low and medium luminances and 10^{-1} cd/m^2 at high luminances.

<center>3. MODELLING THE DATA</center>

The Mulligan and Stone model used in our analysis has two stages. The first stage is a lowpass filter which simulates a band-limited video amplifier. The second stage is the instantaneous standard gamma nonlinearity.

In the first stage, the 8 bit image was passed through an exponential filter with a time constant tau. This process can be represented by the following equation:

$$V(t) = V_{final} + (V_{init} - V_{final}) * \exp(-(t - t_0) / tau) \tag{1}$$

where V(t) is the output voltage of the video amplifier as a function of time, V_{final} is the target voltage of the current pixel, V_{init} is the initial voltage or the voltage of the previous pixel, t_0 is the start time of the transition, and t is greater than t_0 and less than the beginning of the next pixel. Our results from the nonlinear regression show that the tau is about 16.3 ns for the 14" monitor and about 2.8 ns for the 19" monitor. In the model, this function was used as the first stage lowpass filter (Fig. 2). Notice that as the time constant gets smaller, the dashed line gets closer to the solid line in Fig. 2.
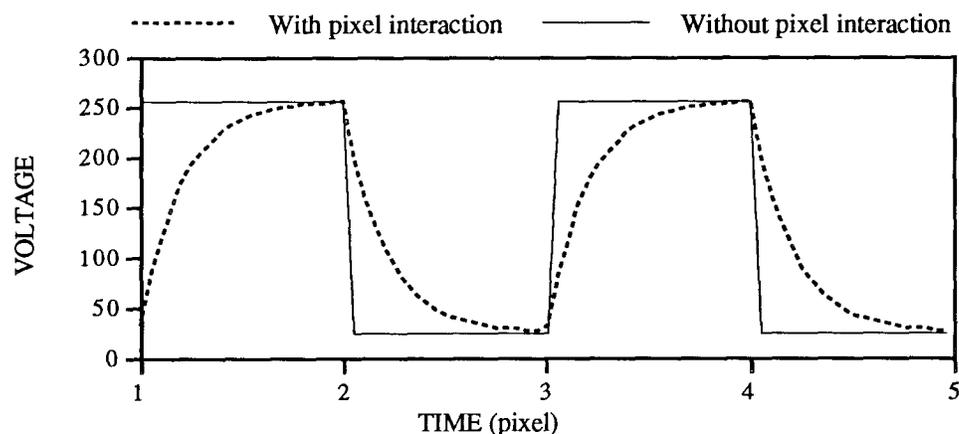

Figure 2. Voltages of one test pattern are plotted as a function of time

In the second stage, the output from the first stage goes through a gamma nonlinearity with the form:

$$L(t) = A * (V(t) - v_0)^\gamma + L_0 \qquad \text{for } V(t) > v_0 \tag{2}$$
$$= L_0 \qquad\qquad\qquad \text{for } V(t) \le v_0$$

where the luminance (L) at time t is a function of voltage at time t (from Eq. 1), γ is the gamma value, v_0 is the voltage offset, L_0 is the luminance for zero applied voltage (or the background luminance) and A is a constant corresponding to the gain of the monitor. Fig. 3 shows the luminance trace after the gamma nonlinearity. Because of the accelerating gamma, the mean output luminance is less than the intended luminance. Notice that the output voltage from the first stage (Fig. 2) has the same mean value before and after the lowpass process. It is the combined effect of the lowpass filter and the gamma nonlinearity that produces the adjacent pixel nonlinearity.
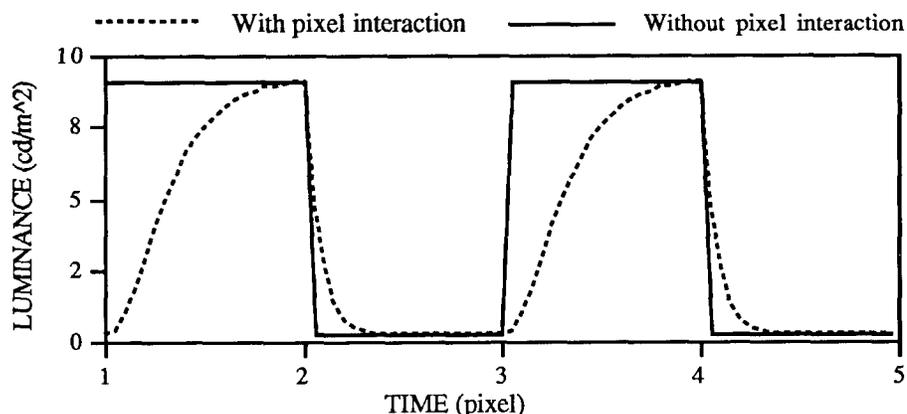

Figure 3. Luminances of the same test pattern are plotted as a function of time

4. RESULTS AND DISCUSSIONS

4.1. Goodness of the fit of the model to the data

For each setting of the monitor's contrast and brightness knobs, the parameters (A, v_0, γ, L_0 and tau) in Eqs. 1 and 2 were obtained by a nonlinear regression to fit the luminances measured for the 50 test patterns for the two monitors. The calculation was done using MATLAB. Table 1 shows the values of the parameters and their error bars from the nonlinear regression. The error bars are produced by a modification to the MATLAB program (write to Klein for details). The last column shows the root mean square errors in cd/m^2. In order to illustrate how well the model can predict the data, the differences of the data and the model were plotted as a function of measured luminances (Fig. 4). The ordinate is the difference between the measured and predicted luminance. We can see that the model fit the data very well.

As a comparison, we fit the same data without considering the pixel interaction by setting the value of tau to zero so that only the standard gamma nonlinearity was used in the nonlinear regression. Figure 5 shows that the resulting errors between the data and the prediction are much higher than the resulting errors when the time constant tau was floated (Fig. 4). In Fig. 4, the range of the ordinate is one fifth that of Fig. 5 to show the small prediction errors. This shows that there are pixel interactions along the raster direction. These interactions can not be described and corrected by a standard LUT.
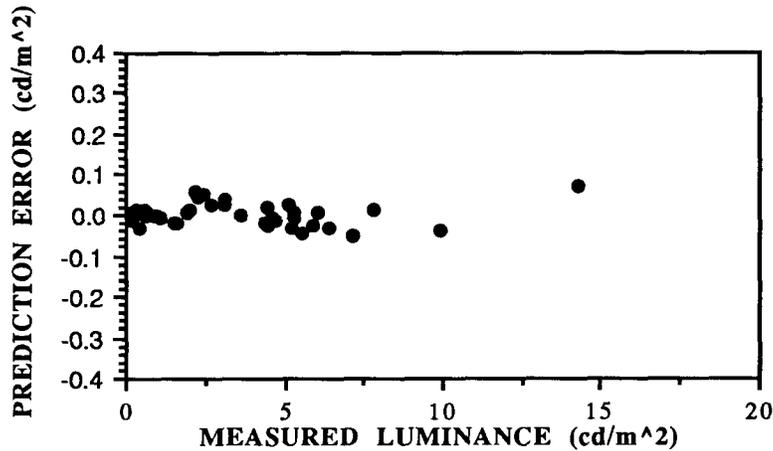
Figure 4. Model fit to data collected at one knob settings of the 19" monitor.
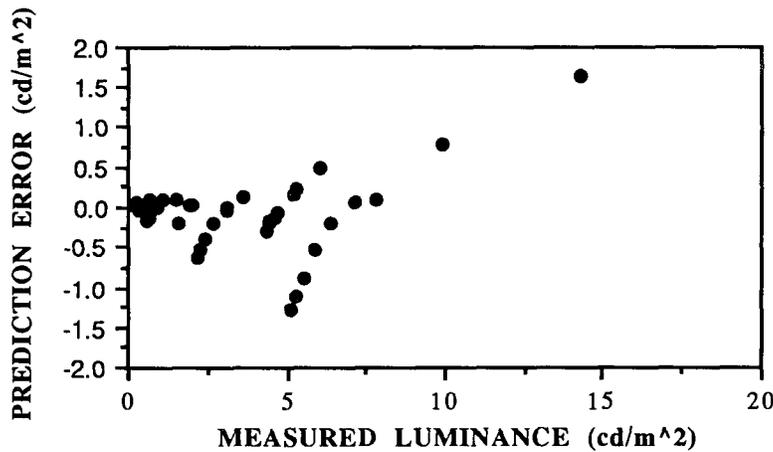

Figure 5. Non-model fit (using only the gamma correction) to the same data in Fig. 4.
The range of the ordinate is five times that of Fig. 4.

TABLE 1. Parameter values from the nonlinearity regression to the data collected from the two monitors.

KNOB SETTINGS	TIME CONSTANT	A	Gamma	Lo (cd/m^2)	v 0	RMSE (cd/m^2)
14" Contrast MAX & Brightness MIN	0.51±.09	15.5±.1	1.57±.02	0.310±.013	0.102±.006	0.019
19" Contrast MAX & Brightness MIN	0.197±.002	24.0±.3	2.32±.03	0.161±.008	0.206±.007	0.031
19" Contrast MAX & Brightness MAX	0.210±.003	26.1±.9	2.31±.05	0.280±.029	0.066±.014	0.176
19" Contrast MIN & Brightness MAX	0.204±.002	1.9±.1	2.64±.05	0.013±.001	0.120±.013	0.005

From Table 1, we can see that, compared to the 19" monitor, the 14" monitor has a significantly longer time constant [16.3 (32*0.51) vs. 2.8 (14*0.2) ns] and less steep gamma value (1.57 vs. 2.32). For the 19" monitor, the different settings of the contrast and brightness knobs do not affect the values of the time constant and gamma significantly. When keeping the contrast constant, increasing the brightness from minimum to maximum decreases the voltage offset (v_0) from 0.206 to 0.066 and increases the background luminance (the luminance for zero

applied voltage) from 0.16 to 0.28 cd/m^2. When holding the brightness knob constant, increasing the contrast from minimum to maximum increases the constant A from 1.9 to 26.1 and also increases the background luminance from 0.01 to 0.28 cd/m^2. In other words, the data show that the contrast knob of the monitor is associated with the gain, A, in Eq. 2 and the brightness knob is associated with the voltage offset (v_0).

4.2. Reliability test of our measurements and higher luminance samples

The first two rows in Table 2 show the parameter values obtained by fitting the data collected on two different days under the same maximum contrast, minimum brightness knob settings. The values agree well for all the parameters (within standard errors) except for the background luminance (L_0). Because the two sets of measurements were made on two different days, it is not surprising that the background luminance would be different. The third row in Table 2 shows the parameter values obtained by fitting data collected at a set of higher sampling luminances with the same knob settings (see Method). The parameter values are very close. The slight changes in parameter estimates is probably because Eq. 2 is not a perfect representation of the gamma nonlinearity. At high luminances the gamma is slightly lower.

TABLE 2. Parameter values from the model fit to data of repeated measurements.

TEST CONDITIONS	TIME CONSTANT	A	Gamma	Lo (cd/m^2)	v0	RMSE (cd/m^2)
LOW SAMPLING LUMINANCE	0.198±.002	24.0±.3	2.36±.03	0.120±.007	0.200±.007	0.023
LOW SAMPLING LUMINANCE	0.197±.002	24.0±.3	2.32±.03	0.161±.008	0.206±.007	0.031
HIGH SAMPLING LUMINANCE	0.198±.003	25.7±.7	2.25±.06	0.190±.022	0.210±.023	0.037

4.3. Nonlinearity and pixel contrast

As we mentioned earlier, the larger the luminance jump between adjacent pixels along the raster, the bigger the nonlinearity. That is, as the pixel contrast increases, the deviation from ideal will increase. We measured the luminances at different pixel contrasts around the mean luminance by using a test pattern consisting of 2 pixel test lines that repeat along the raster direction. The luminances of the two pixels were varied around the mean luminance at contrasts of 0, 25, 50, 75, 90 and 100%. If the pixels had 0% contrast (mean luminance), there is no transition. If the contrast is 100%, it is the transition from zero to maximum luminance. It is important to note that we corrected the monitor gamma before computing the voltage for a given pixel contrast. This is done by creating a standard LUT using Eq. 2 with the parameter values obtained in the nonlinear regression for the data measured at a knob setting of maximum contrast and minimum brightness. The luminances were quantized to 8 bit LUT addresses and the LUT output became the 8 bit DAC voltages. With this standard LUT, we can find the voltages for the mean luminance and luminances at different contrasts. For example, at 50% contrast, the luminance of one pixel is set at 50% lower than the mean luminance and the luminance of the next pixel is set at 50% higher than the mean luminance. The standard LUT was used to find the corresponding voltages that were used in the test pattern.

The luminance at each contrast around the mean luminance was measured for a test pattern along or against the raster. All the measurements at different contrasts were done under the same knob settings as mentioned above. In Fig. 6, measured luminances of test patterns alternating along the raster and non-raster were plotted as a function of contrast. If there were no adjacent pixel nonlinearity, the curve would be a flat line with a constant mean luminance because no matter what contrast was set between the two pixels, the average luminance would still be the mean luminance assuming the luminance of pixels are independent of each other. This is true in the non-raster direction but this is not true in the raster direction.
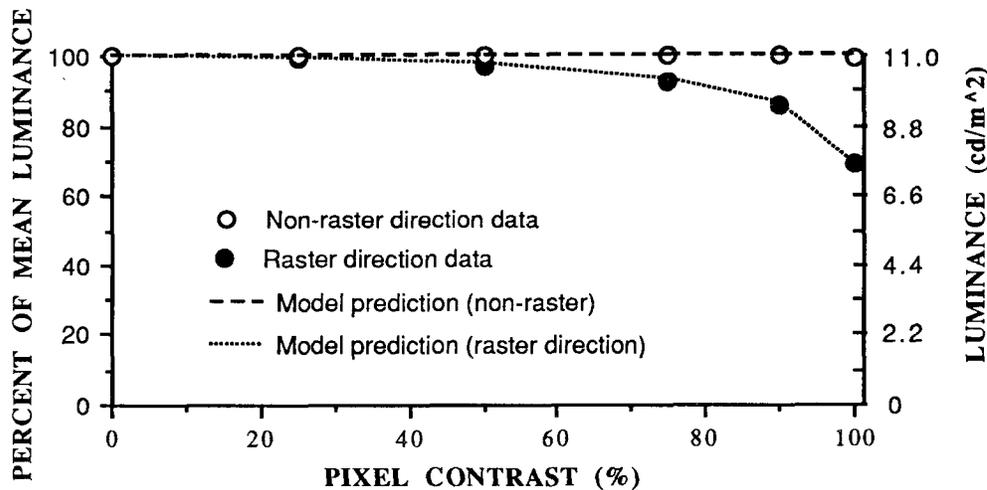
Figure 6. Measured luminance as a function of pixel contrast for one monitor.

In Fig. 6, the open circles show data measured with test patterns in the non-raster direction. As expected, there is no interaction between raster lines so the curve is flat. The dashed line linking the data is the model prediction when the time constant is set to zero (without any adjacent pixel nonlinearity). For the test patterns alternating along the raster (shown by the solid circles), the luminance starts to drop below the mean luminance as the contrast increases, and the biggest deviation occurs at 100% contrast. This data show that the adjacent pixel nonlinearity at high contrast can make the measured luminance 30% lower than the intended luminance. Overall, the model (dotted and dashed line) fits the data very well. For example, for the data in the raster direction, the difference between the data and the model at 50 ,75, 90 and 100% contrast are 1.6%, 1%, 1% and 1%. The sources of the error include measurement errors (about 0.5%) and the LUT quantization error (also about 0.5%).

4.4. Higher order effect and direction of the raster

Table 3 shows results using test patterns consisting of four different luminance levels when both contrast and brightness knobs were set to maximum. One such test pattern, for example, has voltages: L2:25, L5:102, L7:191 and L8:255 (second column). The two "paired" test patterns have the same transitions but in reversed direction of the raster. The last row shows the differences in cd/m^2 between the measured luminances of the paired test patterns for the 19" monitor. The differences are very small showing that it is a very subtle effect and it depends on the magnitude of transitions within the test pattern. The biggest difference occurs at the largest transition (the second pair, from L1 to L8) and the smallest difference occurs at the smallest transition (the third pair, from L4 to L7). The main effect shown in Fig. 6 is much bigger, therefore we call this a higher order effect. The reason the asymmetry is so small will be discussed in a future paper.

TABLE 3. Data showing higher order effect.

TEST PATTERNS	L2-L5-L7-L8	L1-L4-L7-L8	L4-L5-L6-L7	L5-L6-L7-L8
Measured luminance	4.542 ± .012	4.745 ± .013	1.99 ± .01	5.382 ± .007
Measured luminance (Reversed)	4.519 ± .007	4.702 ± .007	1.98 ± .01	5.365 ± .003
DIFFERENCES	0.023±.014	0.043±.015	0.01±.014	0.017±.008

The luminance produced by the asymmetric stimuli in Table 3 depends on the raster direction. In our model, the direction of the raster was specified as from the left to right. The model's prediction for the paired data in Table 3 agrees well with the data. If, however, we reverse the direction of the raster in the model, RMSE would have the opposite sign and would disagree with the data in Table 3. The direction of the raster matters because a high to low transition in the left to right raster direction would be a low to high transition in the reversed raster direction.

4.5. Are the time constants in the model in agreement with the manufacturer's specification?

According to the manufacturer, the time between pixels along the raster is 14 ns for the 19" monitor. Our model gives a tau of 0.2 which gives the time constant of the video amplifier to be about 2.8 ns. The manufacturer's specification for the time constant of the video amplifier is about 2.2 ns. Our model's prediction for the time constant is close to the manufacturer's specification (within 30%). Notice that the time constant is not the same as the risetime (time to go from 10% to 90%) specified by display manufacturer. It can be shown that the risetime is about 2.2 times the time constant. For clarity, we will use time constant instead of risetime in this paper.

For the 14" monitor, the model prediction of the time constant is about 17.8 ns while the manufacturer's specification gives a time constant of 8.2 ns, about one half of our model prediction. The same amount of discrepancy was reported by Mulligan and Stone[1] for a different monitor. We do not understand this discrepancy.

5. CORRECTING THE SPATIAL NONLINEARITY

The problem with the adjacent pixel nonlinearity is that at any luminance transition along the raster direction the luminance of the pixel at the transition is either too dark or too light depending on the direction of transition. This can be easily understood by looking at the Fig. 3 dashed line. At the transition from dark to light, the luminance for pixel 1 (integrating from t=1 to t=2) is less than the maximum (its intended value). At the next transition, from light to dark, the luminance for pixel 2 is larger than the minimum (its intended luminance).

The method we are using to correct this adjacent pixel nonlinearity is straightforward. We employ a two-dimensional LUT which is specified by the intended luminance (LUT address) of the present pixel and the voltage (LUT value) of the preceding pixel. The output of the new LUT is the adjusted voltage for the current pixel which compensates for the adjacent pixel nonlinearity and gives the correct average luminance for that pixel.

5.1. Producing the two-dimensional LUT

There are three steps in making the new LUT:

Step 1. Estimate the parameters of the spatial nonlinearity. We measured the luminance for a large number of repetitive patterns with sharp jumps in the raster direction. These patterns should cover the full range of contrasts and mean luminances. We then carried out a nonlinear regression to estimate the five model parameters: tau, A, v_0, γ, L_0. This step was discussed in detail in the above sections.

Step 2. Generate luminance table. Calculate the average luminance of the current pixel for all combinations of previous and current voltages, $V_{previous}$ and $V_{current}$. This is given by:

$$L_{ave}(V_{previous}, V_{current}) = \int_{t_0}^{t_f} dt\, L(t) \; / \int_{t_0}^{t_f} dt \qquad (3)$$

where t_0 and t_f are the initial and final times for that pixel, so that the average is taken over a single pixel. The integral in the denominator is T (the time it takes to scan a single pixel) which is needed for normalization. The instantaneous luminance L(t) is given by Eqs. 1 and 2. For the purposes of generating a LUT it is convenient to have the luminance levels converted from cd/m^2 to the range from 0 to 255. This is accomplished by the transformation that takes a luminance, L, in cd/m^2 and converts them to L_q (quantized luminances) in an 8 bit range of numbers:

$$L_q = (L - L_{min}) * 255 / (L_{max} - L_{min}). \qquad (4)$$

where L, L_{min} and L_{max} are in units of cd/m^2. L_{min} and L_{max} are

$$L_{min} = L_{ave}(0, 0) = L_0 \qquad (5)$$
$$L_{max} = L_{ave}(255, 255) \qquad (6)$$

where $L_{ave}(V_{previous}, V_{current})$ is the table specified by Eq. 3. Note that although L_q goes from 0 to 255 it is a floating point number rather than an integer. This is especially important for accuracy at low luminances.

Step 3. Inverting the luminance table to generate the LUT. Eq. 3 gives the luminance as a function of the voltage (the value output by the video digital to analog converter VDAC). What is needed is the inverse function (one line of MATLAB code) which gives the voltage as a function of intended luminance. The new element in taking the inverse is that the voltage of the previous pixel $V_{previous}$ must also be specified. The values of the parameters from Eqs. 1 and 2 were used to create a standard LUT (Table 4) and the two-dimensional LUT (Table 5).

TABLE 4. A few cells of a standard LUT.

ADDRESSES	0	11	17	34	51	*85*	102	119	170	187	204	221	255
VOLTAGES	0	105	116	138	154	*179*	189	199	223	230	237	243	255

TABLE 5. A few cells of the two-dimensional LUT.

		LUMINANCE OF THE CURRENT PIXEL						
		11	17	34	*85*	119	187	221
VOLTAGE	105	105	119	146	194	218	255	270
OF THE	116	102	116	143	193	216	253	269
PRECEDING	138	95	110	138	188	212	250	265
PIXEL	*179*	76	95	127	*179*	204	242	257
	199	59	84	120	174	199	238	253
	230	4	60	106	165	191	230	247
	243	-31	42	99	161	188	227	243

Table 5 shows a few rows and columns of the new 256 by 256 LUT resulting from the above process. Both the intended luminances and the voltages are 8-bit numbers. For each intended luminance (top row) at a given pixel, instead of finding its corresponding voltage in the standard LUT, we first get the voltage of the previous pixel (first column), then look across to the column headed by the intended luminance. That value is the output of the two-dimensional LUT. Consider first the case in which the voltage doesn't change across pixels. For example, suppose the intended current pixel luminance is 85 corresponding to a standard voltage of 179 (see Table 4, italic). Table 5 shows that when the previous voltage is 179 (left column, italic) and the intended luminance is 85 (first row, italic), the LUT entry is indeed 179 (middle row, italic) as expected. If, however, the voltage of a previous pixel is smaller than 179 (for example, 105), then the corrected voltage output from our LUT would be greater than 179 because the previous pixel is darker than the current one and there is a dark to light transition. Therefore, the current pixel will have a larger voltage ($V_{current}(105,85)$ = 194) to get the correct average luminance for that pixel. When the luminance of the previous pixel is greater than the current pixel, the new LUT will give a smaller voltage. The larger the difference (larger transition), the greater the difference between the intended voltage and the compensated voltage will be.

5.2. The "ringing effect"

The voltage compensation produces a ringing or luminance oscillation when compensating for an edge. For example, consider an edge presented in the non-raster direction that goes from dark to light. The first light pixel voltage is set to be higher than its intended voltage so that the average luminance of that pixel is what it is intended to be. The next pixel voltage will be lower than it would be because the preceding pixel has higher voltage. The third pixel voltage would be slightly higher than it would be because the second pixel has lower voltage and so on. Therefore, the subsequent pixels after the first pixel will alternate being below and above the nominal voltage in a damped oscillation. To put this in a numerical form, suppose the voltages for a edge using a standard LUT is (assuming 0 for minimum and 255 for maximum):

<pre>...51 51 51 51 204 204 204 204 ...   regular edge</pre>

Our LUT with spatial nonlinearity correction for the same edge would be:

<pre>...51 51 51 51 **232 195 206** 204 ...   corrected edge</pre>

In order to determine the visibility of this oscillation, psychophysical experiments were done by placing the compensated edge (using the two-dimensional LUT as shown in Table 5) abutted to a regular edge (using a standard gamma LUT as shown in Table 4). Pixel size was varied by changing the viewing distances. Three observers were asked to detected the "ringing" at different pixel sizes. The result shows that the oscillation was invisible for pixel sizes less than 0.8 min. A slight vernier offset was visible between the abutting edges even with a 0.8 min pixel size. This is due to an error in the regular edge rather than the compensated edge. All three observers reported that the compensated edge looked sharper.

The problem with the above two-dimensional LUT is that not all luminance transitions can be compensated. There are a few values in the new LUT that are impossible (the lower left and upper right corners) because they are either below zero or above 255. When the transition is very large (low-to-high), there is not enough voltage to compensate for the luminance loss because the values would exceeds the maximum voltage of 255. Similarly, when the transition is from high-to-low, the desired voltage would be less than the minimum voltage of zero. The solution for this problem is beyond the scope of this paper and will be discussed in our future paper.

The advantage of our LUT with the adjacent pixel nonlinearity correction is that it takes into account the adjacent pixel interaction and gives the corrected luminances for image regions with high contrast and high spatial frequency. This correction results in a sharp and accurate image.

6. CONCLUSION

The spatial nonlinearity can be modelled quite successfully by the model proposed by Mulligan and Stone[1]. It can be compensated by a two-dimensional LUT and when the pixel size is small this compensation would correct the wrong luminances in the high contrast, high frequency regions of an image and result in a sharper image.

7. REFERENCES

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