



Australian Government
Department of Defence
Defence Science and
Technology Organisation

Identification of Text and Symbols on a Liquid Crystal Display Part I: Characterisation of the Luminance, Temporal and Spectral Characteristics

Kingsley Fletcher and Stuart Sutherland

Maritime Operations Division
Defence Science and Technology Organisation

DSTO-TN-0770

ABSTRACT

This report outlines the measurements performed on an Apple M9179LL / A 30' 2560 x 1600 LCD panel to establish its luminance response function, luminance uniformity, luminance temporal stability, response time and spectral characteristics. The results of this report were used in subsequent reports (Fletcher, Sutherland, & Nugent, in press; Fletcher, Sutherland, Nugent, & Grech, in press) which examined the minimum character size that allowed for fast and accurate identification of numbers, letters and combat symbology under ambient lighting conditions experienced in naval operations rooms.

RELEASE LIMITATION

Approved for public release

Published by

*Maritime Operations Division
DSTO Defence Science and Technology Organisation
PO Box 1500
Edinburgh South Australia 5111 Australia*

*Telephone: (08) 8259 5555
Fax: (08) 8259 6567*

*© Commonwealth of Australia 2008
AR-013-964
February 2009*

APPROVED FOR PUBLIC RELEASE

Identification of Text and Symbols on a Liquid Crystal Display Part I: Characterisation of the Luminance, Temporal and Spectral Characteristics

Executive Summary

Liquid crystal display (LCD) screens are increasingly being used in a range of applications, including military systems, which have traditionally used cathode ray tube (CRT) displays. LCD screens differ in many characteristics from CRT screens, but many of the military specifications relating to the display of information on computer screens are based on CRT technology. An empirical study was performed which aimed to identify the minimum text and symbol display size that maintained a high level of legibility on modern LCDs. The study required that letters, digits and symbols be displayed in the centre of an LCD at a known luminance level in front of a background of uniform luminance for a fixed duration. Prior to doing this, the luminance characteristics of the LCD needed to be understood. This report outlines the luminance characterisation measurements taken on a 30" 2560 x 1600 pixel Apple LCD.

Measurements were initially performed to establish the uniformity of luminance across the LCD screen. These revealed luminance variations of approximately $\pm 30\%$ around the mean luminance. In order to reduce this variation, the display level of each screen pixel necessary to achieve a uniform level of uniformity was calculated, and the application of this correction resulted in the luminance variation across the LCD screen being reduced to between $\pm 6\%$ and $\pm 17\%$, depending upon backlight brightness.

Screen-centre luminance was observed to increase by 50% over 1.5 hour period after switch-on. However, after this initial warm-up period, screen luminance generally varied by less than $\pm 4\%$ around the mean in an air-conditioned office environment.

Measurements of display durations revealed that the experimental software could reliably control the number of frames periods that a stimulus was displayed for, but that the LCD had a rise time that ranged between 10 ms and 12 ms, depending on the character grey level, or RGB level displayed. Measurements of the luminance of stimuli that varied in size but had identical grey levels revealed that the per-pixel luminance of stimuli did not vary with stimulus size. Measurements were also taken of the LCD spectral emission characteristics.

These measures provided the information needed to construct the stimuli that were used in the study examining minimum text and symbol sizes on the ANZAC ASMD consoles. They also highlighted the fact that the relative luminance of the red, green and blue display colours is not equal, with blue exhibiting a particularly low relative luminance for the same grey level value compared to red and green. Thus, grey level equivalence should not be used as the basis for displaying stimuli of different colour and pure blue may not be appropriate for use on the LCD.

Contents

1. INTRODUCTION.....	1
2. SPECTRAL EMISSION CHARACTERISTICS.....	1
2.1 Materials	1
2.2 Procedure	1
2.2.1 Spectral Characteristics of Red, Green, Blue and White	1
2.2.2 White Spectrum at a Range of RGB Levels.....	2
2.3 Results	2
2.3.1 Spectral Characteristics of Primary Red, Primary Green, Primary Blue and White.....	2
2.3.2 White Spectrum at a Range of RGB Values.	3
3. DISPLAY TIME TEMPORAL RESOLUTION AND ACCURACY	5
3.1 Materials	5
3.2 Procedure	6
3.3 Results	6
4. SOURCES OF VARIATION IN MEASURED LUMINANCE	8
4.1 Measurement Variation due to the Luminance Meter.....	8
4.2 Luminance Variation of the LCD Over Time	8
4.2.1 Materials	8
4.2.2 Procedure.....	8
4.2.3 Results	9
4.3 Luminance Variation due to Changes in Displayed RGB Level	11
4.3.1 Materials	11
4.3.2 Procedure.....	11
4.3.3 Results	11
5. UNCORRECTED LUMINANCE UNIFORMITY	13
5.1 Materials	13
5.2 Procedure	13
5.3 Results	14
5.3.1 Minimum Backlight Brightness.....	14
5.3.2 Maximum Backlight Brightness	15
6. LCD LUMINANCE RESPONSE FUNCTION	16
6.1 Materials	17
6.2 Procedure	17
6.3 Results	17
6.3.1 Minimum Backlight Brightness.....	17
6.3.2 Maximum Backlight Brightness	20

7. VERIFICATION OF LUMINANCE CHARACTERISATION	21
7.1 Materials	21
7.2 Procedure	21
7.3 Results	21
7.3.1 Minimum Screen Brightness	21
7.3.2 Maximum Screen Brightness	22
8. LCD LUMINANCE UNIFORMITY CORRECTION.....	23
8.1 Materials	23
8.2 Procedure	23
8.3 Results	23
8.3.1 Minimum Screen Brightness	23
8.3.2 Maximum Screen Brightness	24
9. LUMINANCE OF DIFFERENT SIZED CHARACTERS	24
9.1 Materials	25
9.2 Procedure	25
9.3 Results	25
10. SUMMARY	26
11. CONCLUSIONS.....	28
12. REFERENCES	29
APPENDIX A: EQUIPMENT TECHNICAL SPECIFICATIONS	30

1. Introduction

Liquid crystal display (LCD) screens are increasingly being used in a range of applications, including military systems, which have traditionally used cathode ray tube (CRT) displays. Although LCD screens differ in many characteristics from CRT screens, many of the specifications relating to the display of information on computer screens appear to be based on CRT technology. To address this issue, Fletcher, Sutherland, Nugent and Grech (2009) performed an empirical study to determine the minimum text and symbol size that supported fast and accurate character identification on a modern high-resolution LCD. That study required letters, digits and symbols to be displayed in the centre of an LCD at a known luminance level over a uniform grey background, also of a known uniform luminance level for a fixed duration of approximately 100 ms. The current report outlines the measurements taken on a 30", 2560 x 1600 pixel Apple LCD screen to identify its display characteristics. The current report identifies the spectral distribution of screen emissions, how accurately display time could be controlled, the possible sources of variation in screen luminance, the luminance response function of the LCD and whether the per-pixel luminance varied with stimulus size. It also identifies the uncorrected luminance uniformity of the LCD and the steps taken to improve the uniformity.

2. Spectral Emission Characteristics

In order to quantify the spectral characteristics of the LCD the spectrum of primary red, primary green, primary blue and white (equal RGB levels) were recorded at a fixed RGB level. The spectrum of white was also recorded at a range of RGB levels in order to examine whether the white spectrum changed with luminance levels.

2.1 Materials

An Apple M9179LL/A 60 Hz LCD was used as the display monitor, and the technical specifications of the LCD and computer used are provided in Appendix A. An Ocean Optics S2000 Spectrometer connected to a laptop PC was used to measure and record the LCD spectral characteristics.

2.2 Procedure

2.2.1 Spectral Characteristics of Red, Green, Blue and White

The LCD backlight brightness was set to its maximum. A white bitmap file, RGB (180, 180, 180), was displayed on the LCD in a dark room. The spectrometer was placed over the centre of the screen and its gain adjusted so that the peak measured signal was just less than saturation levels. The spectrum of the display was then captured to file. Without changing the spectrometer gain settings, files of primary red (RGB (180, 0, 0)), primary green (RGB (0, 180, 0)), primary blue (RGB (0, 0, 180)) and black (RGB (0, 0, 0)) were displayed and the spectrum of each captured. The LCD backlight brightness was

then set to minimum and the spectrum of each file measured again. The luminance of each colour at maximum brightness setting was also recorded using the Tectronix J17 photometer.

2.2.2 White Spectrum at a Range of RGB Levels

The LCD backlight brightness was set to maximum and a white bitmap file with RGB code (250, 250, 250), which had an approximate luminance of 280 cd/m², was displayed in a dark room. The spectrometer was placed over the centre of the screen and its gain adjusted to avoid saturation. The spectrum of the display was then captured to file. Again without changing the spectrometer gain settings, bitmap files with RGB codes of (190, 190, 190), (125, 125, 125), (85, 85, 85) and (65, 65, 65) were displayed in turn and their spectrum recorded. These RGB levels corresponded to luminance levels of approximately 150 cd/m², 60 cd/m², 25 cd/m², and 15 cd/m² respectively.

2.3 Results

2.3.1 Spectral Characteristics of Primary Red, Primary Green, Primary Blue and White

The spectral radiance of the LCD at its maximum brightness for white, red, green and blue images for wavelengths between 380 nm and 730 nm, is plotted in Figure 1. The spectrum is very peaky, which is likely to be due to the fluorescent backlighting used in the screen. The plot for minimum brightness is not shown, but it has an almost identical spectral distribution, though with an intensity of approximately one quarter of the maximum brightness. Since the LCD brightness is adjusted by altering the duty-cycle of the fluorescent backlights, the invariance in spectral characteristics between the minimum and maximum brightness settings was expected.

At maximum brightness, the luminance of red (180, 0 0), green (0, 180, 0), blue (0, 0, 180) and white (180, 180, 180) was 32.4 cd/m², 87.5 cd/m², 13.3 cd/m², and 133.5 cd/m² respectively. This corresponds to a RGB weighting of (0.24:0.66:0.10), which is similar to the typical value for CRTs of (0.213:0.715:0.072) (ITU, 1990).

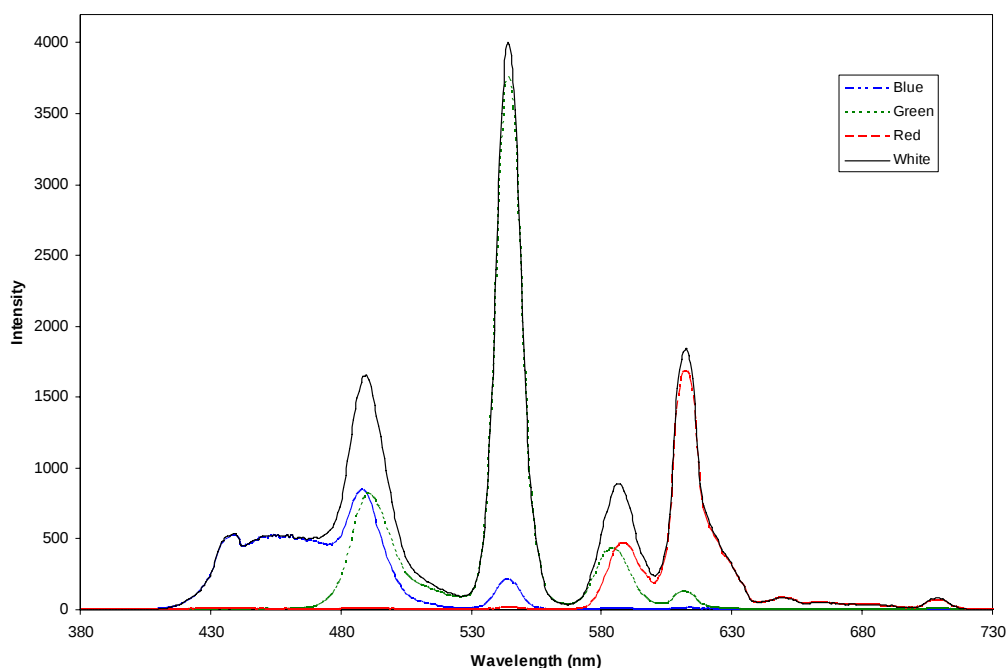


Figure 1. Plot of the spectral emission characteristics of the Apple M9179LL/A LCD monitor at maximum brightness setting for white, red, green and blue displays.

2.3.2 White Spectrum at a Range of RGB Values.

A plot of nominal spectral radiance against wavelength for each RGB level tested is shown in Figure 2. To determine if the relative portions of red, green and blue changed with absolute grey level, the colour coordinates based on the CIE 1964 10-degree XYZ colour matching functions were calculated for each RGB level. The colour coordinates are shown in Table 1.

Table 1: Colour coordinates based on the CIE 1964 10 degree XYZ colour matching functions for displays with RGB levels of (65, 65, 65), (85, 85, 85), (125, 125, 125), (190, 190, 190) and (250, 250, 250)

RGB Level	Colour Coordinates (x,y,z)
65, 65, 65	(.336, .414, .251)
85, 85, 85	(.332, .411, .256)
125, 125, 125	(.335, .413, .252)
190, 190, 190	(.337, .413, .251)
250, 250, 250	(.334, .405, .260)

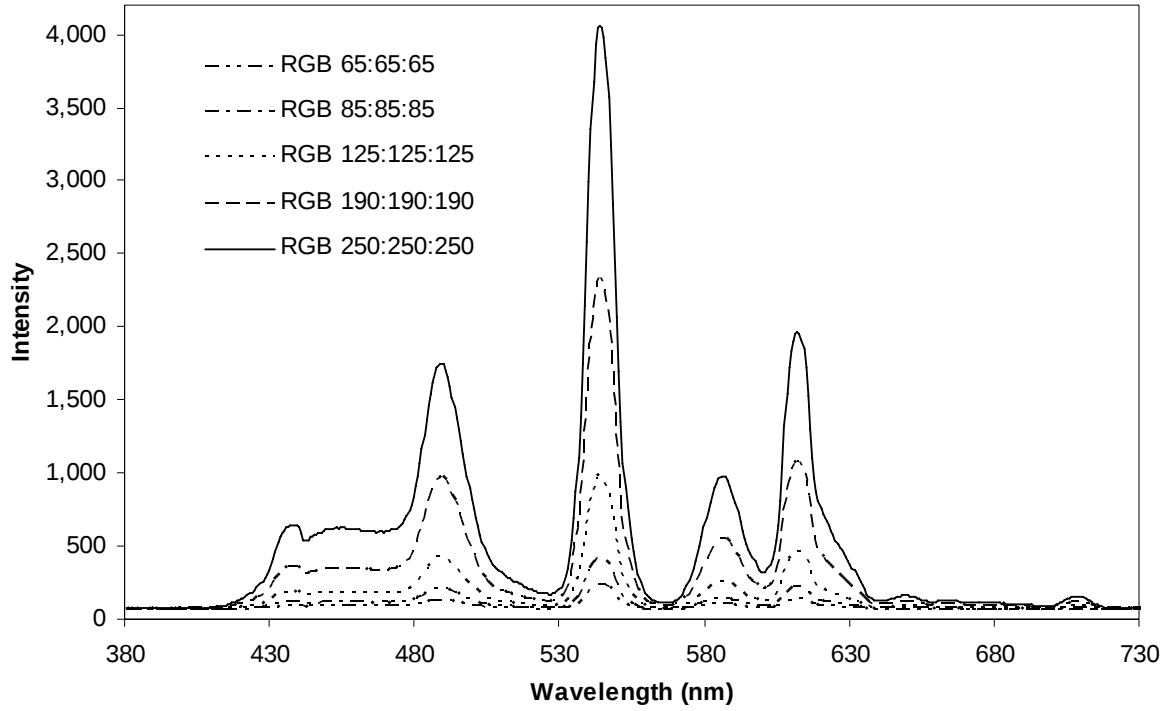


Figure 2: Plot of the spectral emission characteristics of the Apple M9179LL/A LCD monitor for RGB levels of (65, 65, 65), (85, 85, 85), (125, 125, 125), (190, 190, 190) and (250, 250, 250)

The colour differences between white at (125, 125, 125) and all other RGB levels were calculated using the CIE ΔE^*_{94} colour difference formula (CIE, 1995) which defines the total colour-difference as the distance between two colour samples in lightness, chroma, and hue differences, ΔL^* , ΔC^*_{ab} , ΔH^*_{ab} , with weighting function, S_L , S_C , S_H , and parametric factors, k_L , k_C , k_H .

$$\Delta E^*_{94} = \left[\left(\frac{\Delta L^*}{k_L S_L} \right)^2 + \left(\frac{\Delta C^*_{ab}}{k_C S_C} \right)^2 + \left(\frac{\Delta H^*_{ab}}{k_H S_H} \right)^2 \right]^{1/2}$$

The colour difference between white at a mid-range RGB level of (125, 125, 125) and all other levels tested is shown in Table 2, from which it can be seen that, with the exception of (250, 250, 250), the total colour-difference is less than 1.5. Given that ΔE^*_{94} colour differences of around 1.0 are perceptually indistinguishable (Montag & Berns, 1999), it appears that changing luminance by changing RGB levels equally does not substantially affect perceived colour.

Table 2: The ΔE^*_{94} colour difference between white at various RGB levels and RGB (125, 125, 125)

RGB Level	ΔE^*_{94} Colour Difference from RGB (125, 125, 125)
65, 65, 65	0.598
85, 85, 85	1.402
125, 125, 125	0.000
190, 190, 190	0.945
250, 250, 250	3.985

3. Display Time Temporal Resolution and Accuracy

The text and symbol size study required that visual stimuli be displayed at the centre of the LCD for a period of approximately 120 ms. While the display time did not need to be precisely 120 ms, it was important that the actual display duration be known and stable over a range of luminance levels.

The possible display times of a visual stimulus on a LCD screen are determined by its frame rate, with the minimum possible display time corresponding to a single frame, and display times then incrementing in integer multiples of the frame length. The Apple M9179LL/A LCD had a frame rate of 60Hz which implies a minimum display time and display time increments of 16.67 ms. However, LCDs also have a finite rise and fall time which will impact on the actual display duration. It is also possible that an unstable display time will result if the software is not synchronised with the frame rate. To reduce this uncertainty, tests were performed to determine what the actual display time was of an eight-frame display period over a range of luminance levels.

3.1 Materials

An Apple M9179LL/A 60 Hz LCD was used as the display monitor, and the technical specifications of the LCD and computer used are provided in Appendix A. The monitor brightness was set to its maximum. PXLab software was used to control the display duration, and a photodiode connected to a Tektronix TDS3052 digital oscilloscope was used to measure the rise time response. The photodiode has a response time of approximately 1 μ s.

Matlab was used to create four 300 x 300 pixel stimulus bitmap files with RGB levels of (65, 65, 65), (90, 90, 90), (130, 130, 130) and (175, 175, 175), which were consistent with the range used in the text and symbol size study. Two full screen background bitmap files with RGB levels of (10, 10, 10) and (40, 40, 40) were also created.

3.2 Procedure

The background file was initially displayed on the screen. A stimulus bitmap file was then presented in the centre of the screen for an 8-frame (nominally 133 ms) period before being removed. The voltage output of the photodiode over the period from just before to just after the stimulus file presentation was recorded on the oscilloscope. The photodiode voltage was sampled every 10 μ s, and an average of every 25 samples (250 μ s) recorded.

3.3 Results

The duration of each display was calculated in two ways. The first method was to calculate the length of time between when the measured voltage began to increase and when the measured voltage began to decrease. The second method was to calculate the period for which the voltage was within 25% of its maximum value. The results for each method are shown in Table 3.

The average duration between the initial voltage rise and fall points over all display conditions was 132.9 ms, which closely matched the expected display duration of 133.33 ms and showed very little variation (< 1% variation from the mean). When measured as the duration for which the voltage was within 25% of its maximum value, the mean display time of all stimulus bitmap files over a background RGB level of (10, 10, 10) was 121.2 ms, which increased by 2.1 ms to 123.3 ms for a background RGB level of (40, 40, 40). This indicates that the combined rise and fall time varied from 10 ms to 12 ms, depending on the particular combination of stimulus and background RGB levels.

An example of the voltage waveform at minimum backlight brightness is shown in Figure 3 and an example of the voltage waveform at maximum backlight brightness is shown in Figure 4. Note that the method of reducing the backlight brightness appears to be to decrease the mark-space ratio to less than 100%. At minimum brightness, this produces a waveform with a period of 6 ms or a frequency of 167 Hz. This is higher than the critical fusion frequency of the human visual system, which while depending on the modulation and level of adaptation, is typically below 70 Hz.

Table 3: Measured display time for stimulus of four RGB levels as measured with a photodiode. Stimuli were displayed over background RGB levels of (10, 10, 10) and (40, 40, 40). Display time was measured both as the time between initial voltage rise and initial voltage fall, and the time for which voltage was within 25% of its maximum value.

Stimulus R:G:B Level	Time Between Initial Voltage Rise and Fall Points (ms)		Time where Voltage was within 25% of Maximum Value (ms)	
	Background R:G:B Level	Background R:G:B Level	Background R:G:B Level	Background R:G:B Level
	10:10:10	40:40:40	10:10:10	40:40:40
65:65:65	131.78	133.30	121.36	123.76
90:90:90	133.14	133.58	120.38	122.84
130:130:130	133.36	132.78	120.76	122.68
175:175:175	132.86	132.62	122.28	123.74

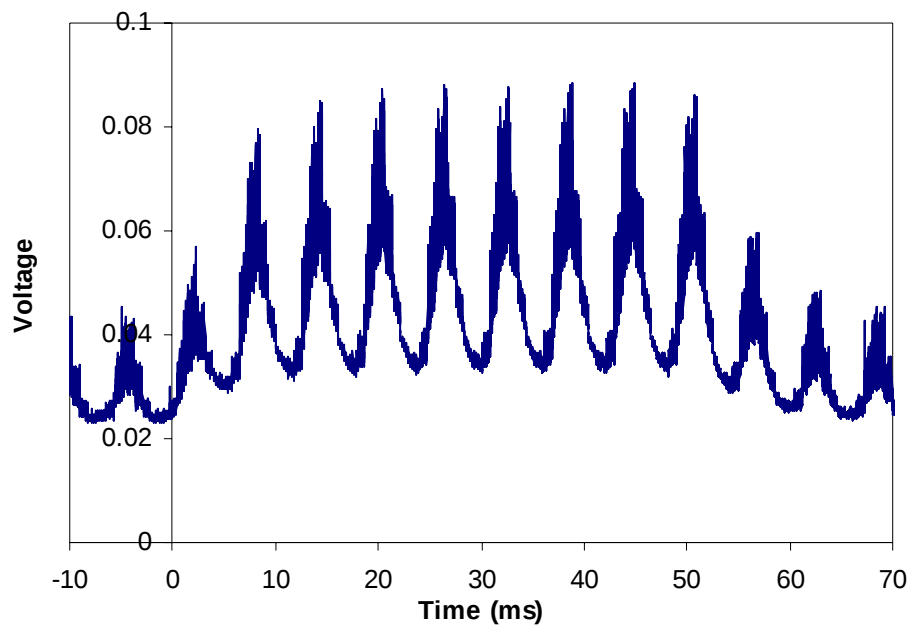


Figure 3: Plot of photodiode voltage waveform when exposed to a 3 frame duration (51 ms) stimulus with the LCD backlight brightness set to minimum

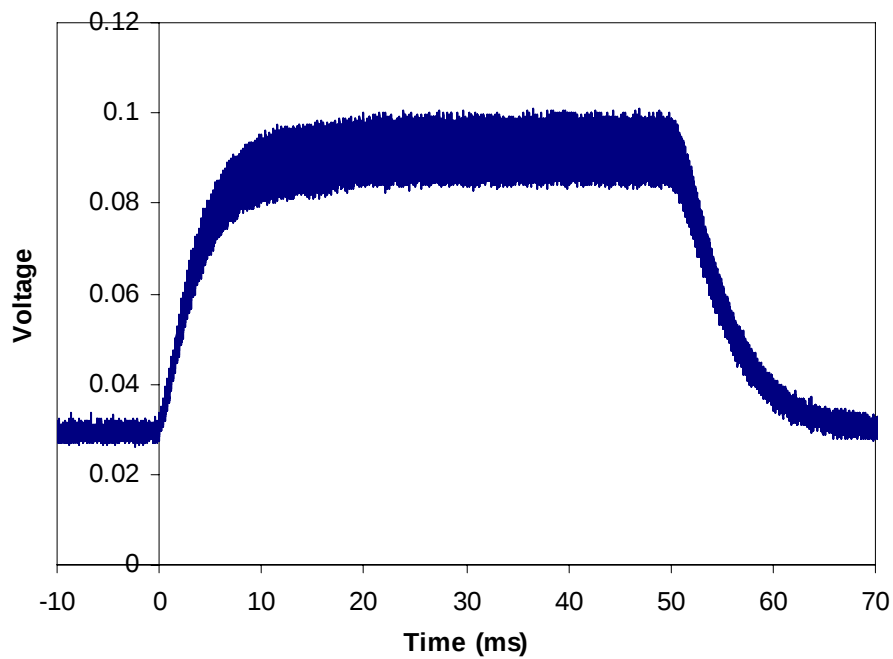


Figure 4: Plot of photodiode voltage waveform when exposed to a 3 frame (51 ms) duration stimulus with the LCD backlight brightness set to maximum

4. Sources of Variation in Measured Luminance

As the text and symbol size study involved presenting visual stimuli on the LCD at known luminance levels, the stability of the luminance levels displayed by the LCD was of interest. Thus measurements were taken to quantify the expected fluctuations in luminance of the LCD. The variation over time and with changes in the displayed RGB levels were measured, however, the luminance meter used was also found to be a source of measurement variation.

4.1 Measurement Variation due to the Luminance Meter

A Tektronix J17 photometer with a J1803 luminance sensor head was used to collect luminance measurements. The sensor head was fitted with a rubber retainer that allowed screen luminance to be measured independently of room ambient lighting levels. The output of the J17 could be logged via a RS-232 port, which provided updated luminance readings at approximately 1 second intervals. It was noted that, even for a stable luminance source, the instantaneous luminance level reported by the J17 varied, so Matlab code was written to allow for an average of a sample of luminance readings to be recorded. The J17 meter also performed an internal recalibration approximately every 21 minutes, after which the measured luminance could change by up to 0.06 cd/m² from the levels measured directly prior to the recalibration. Given that luminance levels less than 0.2 cd/m² were to be measured, this translates into a potential error of 30%. This potential error source in the measurements was minimised by collecting measurements within a 20 minute block between re-calibrations.

4.2 Luminance Variation of the LCD Over Time

The luminance of the LCD was likely to change over time due to fluctuations in screen temperature. An initial increase in temperature was expected in the period between switch-on and when the screen reached its stable operating temperature. Further ongoing fluctuations over time may also be seen in response to changes to ambient air temperature. Measurements were taken of LCD luminance over time to determine the warm-up period during which luminance measures should not be taken, and the expected fluctuations in luminance levels that can be expected over the course of a day.

4.2.1 Materials

The Apple M9179LL/A LCD was used as the display monitor with its brightness set to minimum. Matlab was used to create full-screen bitmap files with RGB levels of (15, 15, 15) and (50, 50, 50), which were used as the screen displays. A Tektronix J17 luminance meter with a J1803 luminance sensor head was used to record screen luminance levels.

4.2.2 Procedure

To determine the warm-up period of the screen, the LCD was first turned off for at least 12 hours. Luminance recording was then started upon power-up and continued until the

luminance level had stabilised. The average of 12 screen-centre luminance readings was recorded every two minutes for the duration of measurement.

To determine the variation in luminance that can be expected due to air temperature variation over the day, measurements were taken between mid morning, after the screen had been on for over two hours, and the end of the day. Again the average of 12 screen-centre luminance readings was recorded every two minutes over the measurement period.

4.2.3 Results

A plot of the luminance measured at the centre of the screen for a bitmap image file with a RGB level of (50, 50, 50) against elapsed time since power-up is shown in Figure 5. From Figure 5 it can be seen that stability in the luminance measures occurred after approximately 1 hour and 20 minutes and that the luminance increased by 48% over this period. Note also the step change in luminance level that occurred between 44 minutes and 1 hour and six minutes elapsed time. This is an example of the effect of the internal recalibration of the J17 discussed in Section 4.1.

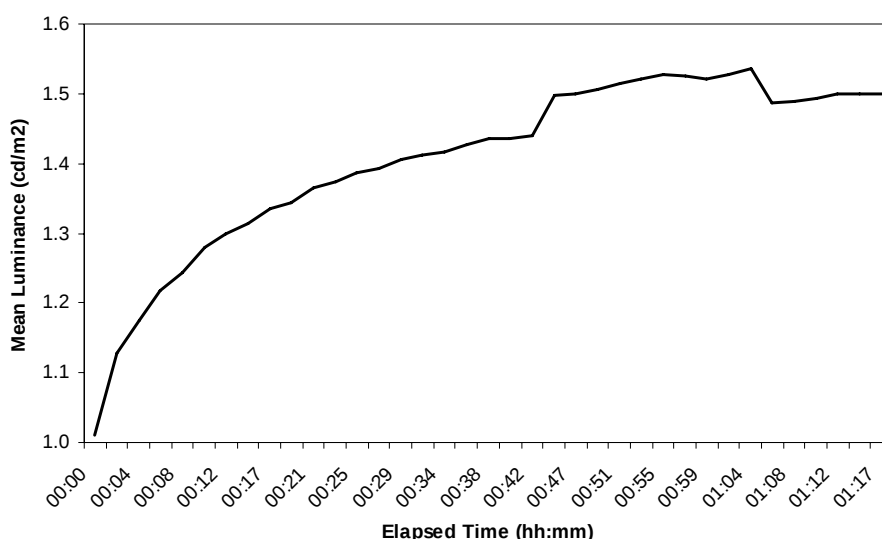


Figure 5: Plot of screen luminance (cd/m²) measured at screen centre against time elapsed since power-up for RGB level (50, 50, 50)

The variation in the screen-centre luminance that occurred after the warm-up period was measured at RGB levels (15, 15, 15) and (50, 50, 50), the results of which are shown in Figure 6 and Figure 7, respectively. The plots of measured luminance again clearly show the J17 recalibration offset effect, where there is a regular block shift in luminance readings. Because this offset is irrelevant to identifying the luminance variation due to temperature, the measured luminance levels were adjusted to remove the effect of the offset. This was achieved by subtracting the difference between the first luminance reading in its calibration block and the last luminance reading in the previous calibration from each luminance reading in a block.

The mean centre-screen luminance for RGB level 15 was 0.20 cd/m^2 , and a variation of $\pm 3.2\%$ was measured over the course of a day. The mean centre-screen luminance for RGB level 50 was 1.56 cd/m^2 , and this RGB level had a variation of $\pm 3.8\%$ measured over the course of a day. Thus it appears that luminance levels may vary up or down by between 3% and 4% over the course of a working day in an air-conditioned environment. It is of interest to note that if the measurement period was extended to 24 hours, a variation of approximately $\pm 6.8\%$ was observed. The sources of this variation were not explored, but possible explanations include ambient temperature or mains supply voltage fluctuations.

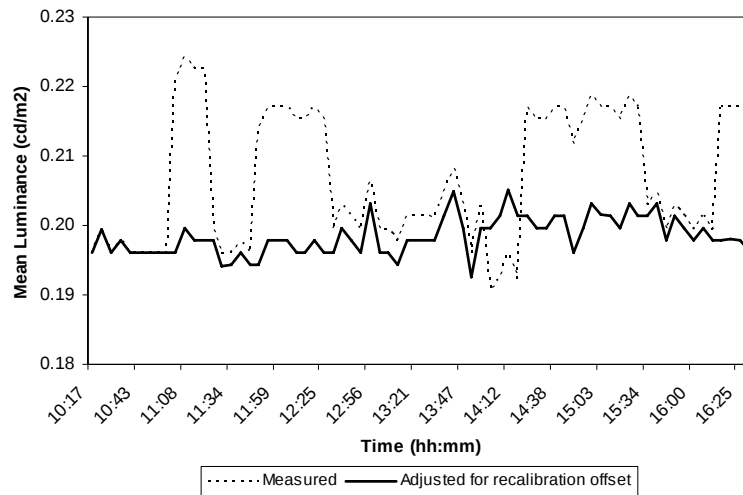


Figure 6: Plot of screen luminance (cd/m^2) measured at screen centre and adjusted to remove the effect of the J17 meter recalibration offset against time for RGB level 15

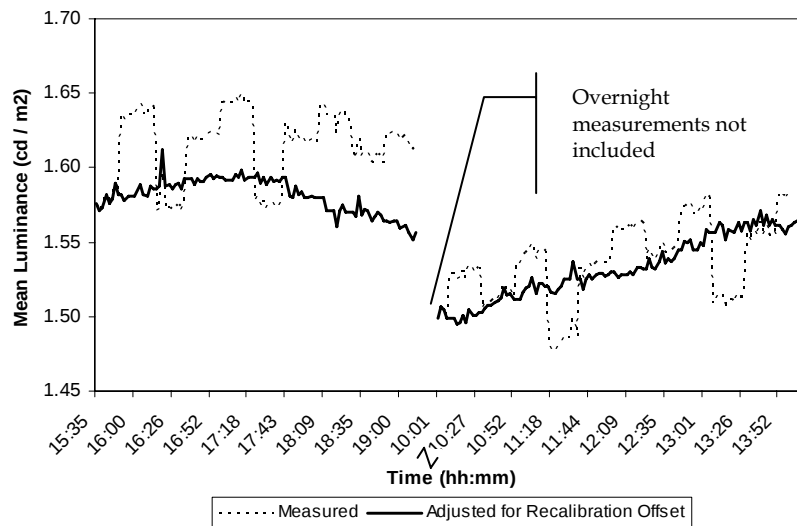


Figure 7: Plot of screen luminance (cd/m^2) measured at screen centre and adjusted to remove the effect of the J17 meter recalibration offset against time for RGB level (50, 50, 50). Measurements taken between 19:11 and 10:01 are omitted from the plot as these times are outside the normal daytime operating range. This omission caused the discontinuity in the plot.

4.3 Luminance Variation due to Changes in Displayed RGB Level

In addition to effects caused by ambient air temperature changes, different brightness levels may generate thermal effects in the screen that may affect luminance levels. This section outlines the measurements taken to characterise the luminance response over time to step changes in the RGB level.

4.3.1 Materials

The Apple M9179LL/A LCD was used as the display monitor; again with the brightness set to minimum. Matlab was used to create full-screen bitmap files with RGB values of (0, 0, 0) and (255, 255, 255). A Tektronix J17 luminance meter with a J1803 luminance sensor head was used to measure screen luminance.

4.3.2 Procedure

After allowing the screen to reach its stable warm-up temperature, the full-screen (0, 0, 0) bitmap file was displayed for three minutes. The full-screen (255, 255, 255) bitmap file was then displayed for 1 hour and 23 minutes. The (0, 0, 0) bitmap file was then restored for 10 minutes, after which the (255, 255, 255) bitmap file was displayed for a further two minutes. The mean of 12 luminance measures was recorded once every minute throughout.

4.3.3 Results

A plot of measured luminance over time during the RGB level changes is shown in Figure 8. Luminance increased from 66.7 cd/m² to 68.2 cd/m² over the 1 hour and 23 minute period over which RGB level (255, 255, 255) was displayed, an increase of 2.12%. It is difficult to unambiguously attribute this luminance increase to thermal changes caused by the step increase in RGB level, as any increase in ambient air temperature over the same period would confound the result. However, when the (255, 255, 255) RGB file was re-displayed after a 10-minute period of RGB level (0, 0, 0), a luminance of 67.8 cd/m² was measured. This level was less than the previously measured (255, 255, 255) RGB luminance, which suggests a partial dissipation of the thermal effects caused by the high RGB level.

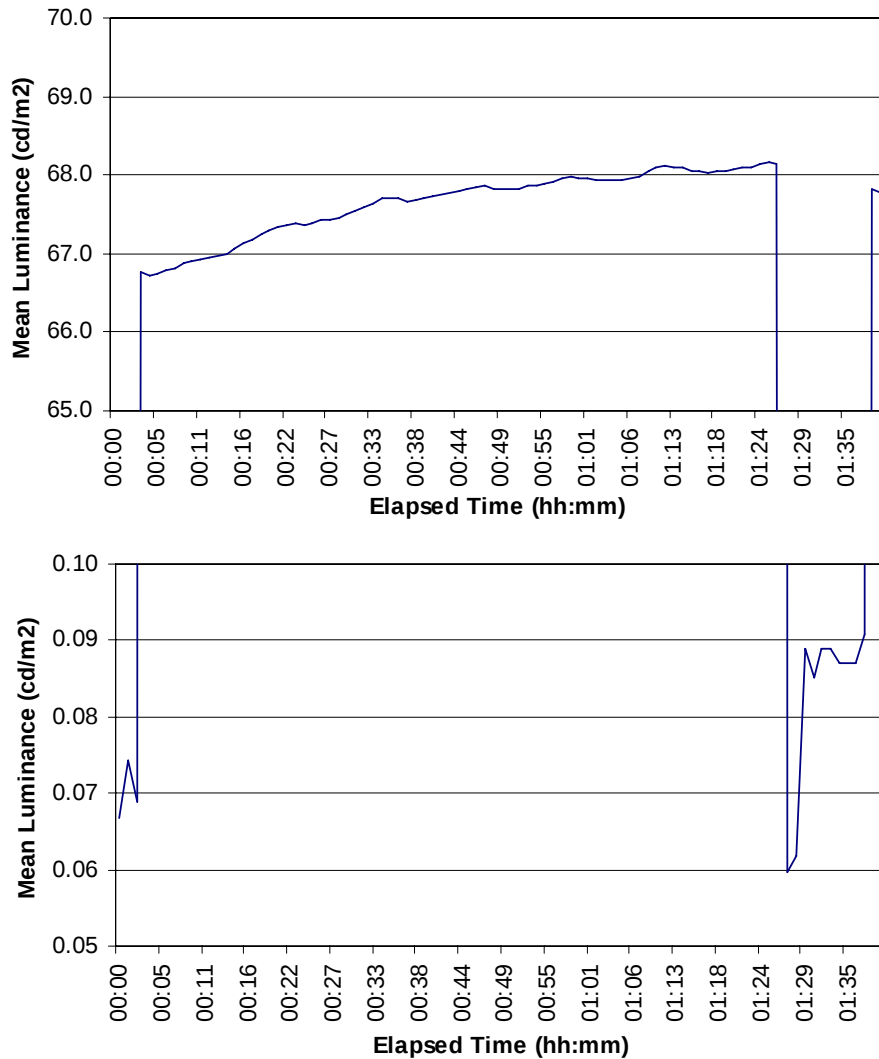


Figure 8: Plot of screen luminance (cd/m^2) measured at screen centre while displayed RGB level was stepped between (0, 0, 0) and (255, 255, 255). The top panel shows the luminance response at RGB level 255 and the bottom panel shows the luminance response at RGB level (0, 0, 0).

The average initial screen-centre luminance at RGB level (0, 0, 0) was 0.070 cd/m^2 . This increased to an average of 0.082 cd/m^2 during the second, 10 minute period of RGB level zero, an increase of 17.9%. While this may be due to increased heat caused by the previous period of RGB level (255, 255, 255), it is again difficult to draw a definitive conclusion. The average luminance level of the second RGB level zero period is within 0.06 cd/m^2 of the first RGB level zero period, which is less than the possible variance due to the meter recalibration offset alone.

Thus while there appears that display duration has some influence luminance, the effect is small, and, when considered in the context of an experiment where high RGB stimuli will only be displayed for a short period, does not appear to be of practical significance.

5. Uncorrected Luminance Uniformity

Measurements were performed to determine the initial, uncorrected, luminance uniformity of the LCD at near-minimum luminance levels. At the minimum backlight brightness setting, the luminance of the brightest point of the LCD when displaying an RGB level of (0, 0, 0) was 0.2 cd/m². At the maximum backlight brightness setting, the luminance of the brightest point of the LCD displaying a (0, 0, 0) RGB level was 1 cd/m². These values were therefore the minimum uniform luminance that could be achieved at each brightness setting. At the minimum backlight brightness setting, a grey level of (10, 10, 10) produced a luminance level of 0.2 cd/m² at the darkest point of the LCD. At the maximum backlight brightness setting, a grey level of (15, 15, 15) produced a luminance level of 1 cd/m² at the darkest point of the display. At the minimum backlight brightness setting a grey level of (40, 40, 40) produced a luminance level of 1 cd/m² at the darkest point of the display. These grey levels were used to explore the uniformity of the LCD luminance at each backlight brightness setting.

5.1 Materials

An Apple M9179LL/A 60 Hz LCD was used as the display monitor, and the technical specifications of the LCD and computer used are provided in Appendix A. Matlab was used to create three 2560 x 1600 pixel bitmap files, with constant RGB levels of (10, 10, 10), (10, 10, 10) and (10, 10, 10). RGB levels of (10, 10, 10) and (10, 10, 10) were chosen as preliminary measures had established that an RGB variation of approximately 10 and 15 occurred across the LCD when set to minimum and maximum brightness levels respectively. A RGB level of (40, 40, 40) was chosen as this produced a screen-centre luminance of approximately 1 cd/m² when the LCD was set to minimum brightness, which was similar to the minimum (RGB = (0, 0, 0)) luminance of the LCD when set to maximum brightness. Screen luminance levels were collected using a Tektronix J17 photometer with a J1803 luminance sensor head which used the CIE photopic curve to derive luminance. The active pixel area of the screen always exceeded the field of view of the photometer when taking luminance measurements.

5.2 Procedure

With the LCD backlight set to its minimum brightness, the RGB (10, 10, 10) and (40, 40, 40) bitmaps were separately displayed on the LCD and the luminance level was measured at 40 screen points arranged in a regular 8 x 5 grid pattern. The measurements started in the top left corner of the screen, and progressed left to right, and top to bottom. The recorded luminance level at each measurement point was the average of a sample of 12 luminance readings. A calibration measurement of the luminance level at the centre of the screen was taken before the first measurement point and after the final measurement point in order to capture any drift in measured luminance over the period of the measurements. This method was repeated at the maximum LCD backlight setting using the RGB (15, 15, 15) bitmap. All points were measured within 20 minutes, which ensured that no meter recalibration occurred during the measurements (see section 4.1).

5.3 Results

5.3.1 Minimum Backlight Brightness

A plot of screen luminance at each of the 40 measurement points for RGB (10, 10, 10) with the LCD set to minimum brightness is shown in Figure 9, and Figure 10 shows the screen luminance at each measurement point for RGB (40, 40, 40). The two plots show a trend, which is stronger for (40, 40, 40) than for (10, 10, 10) for the right-hand third of the screen to have a luminance approximately 30% higher than the left-hand half of the screen. The variation in vertical screen luminance is less, but shows a small trend for luminance to increase from screen bottom to top.

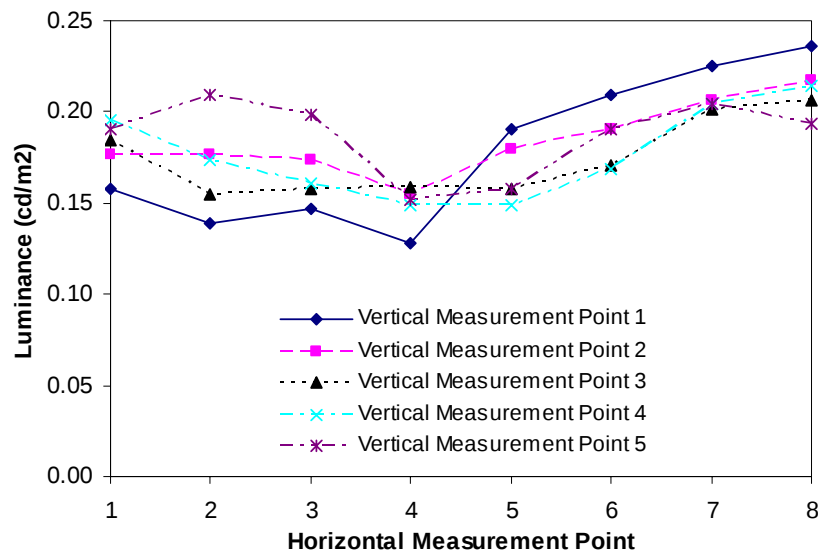


Figure 9: Plot of screen luminance (cd/m²) at each of the 40 measurement points for a RGB (10, 10, 10) display with the LCD set to minimum brightness. The graph plots the horizontal measurement point on the x-axis and has a separate line for each vertical measurement point.

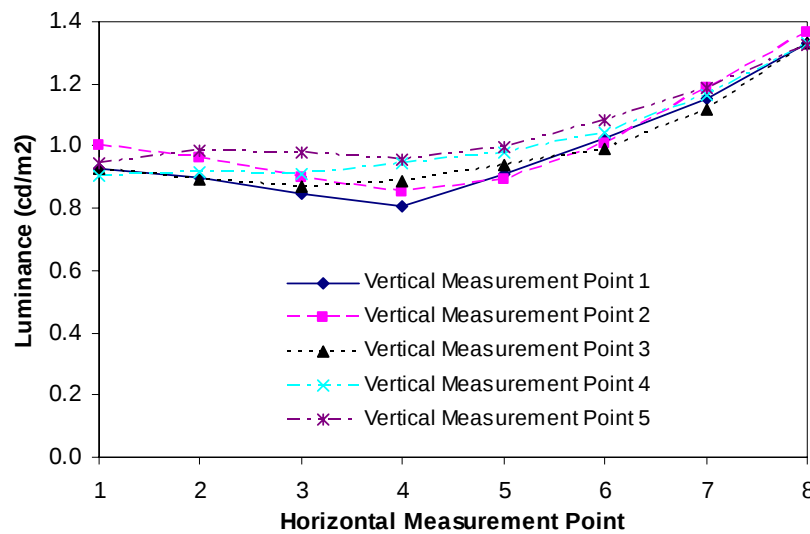


Figure 10: Plot of screen luminance (cd/m²) at each of the 40 measurement points for a RGB (40, 40, 40) display with the LCD set to minimum brightness. The graph plots the horizontal measurement point on the x-axis and has a separate line for each vertical measurement point.

5.3.2 Maximum Backlight Brightness

A plot of screen luminance at each of the 40 measurement points for RGB (15, 15, 15) with the LCD set to maximum brightness is shown in Figure 11. This condition resulted in a more uniform horizontal luminance distribution, but with a greater vertical luminance spread, particularly in the left-hand third of the screen.

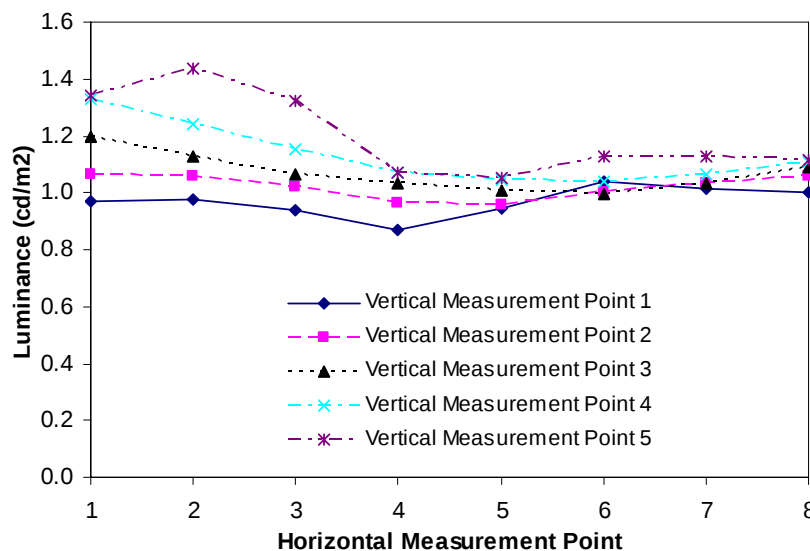


Figure 11: Plot of screen luminance (cd/m²) at each of the 40 measurement points for a RGB (15, 15, 15) display with the LCD set to maximum brightness. The graph plots the horizontal measurement point on the x-axis and has a separate line for each vertical measurement point.

Although this variation in luminance uniformity was within the 170% luminance variation allowed in ISO9241-3 and BSR/HFES 100 an attempt was made to generate a bitmap file with compensatory RGB levels that would result in a more uniform luminance display. To achieve this, the relationship between the RGB input and luminance output of the LCD was characterised at a number of screen points which, via interpolation, would allow the per-pixel RGB level necessary to produce a particular output luminance to be determined.

6. LCD Luminance Response Function

Based on observations of the general shape of the luminance response function, an initial decision was taken to model it using a power function of the form:

$$L = L_0 + (w_r R + w_g G + w_b B)^\gamma \quad (1)$$

Where	L	= Output luminance
	L_0	= Luminance at RGB (0, 0, 0)
	w_r	= Red weighting
	w_g	= Green weighting
	w_b	= Blue weighting
	R	= Input red level
	G	= Input green level
	B	= Input blue level
	γ	= Constant, often in the range 1.8 - 3.0

Thus for known levels of L and RGB, values of L_0 , w_r , w_g , w_b and γ needed to be found to model the luminance response of the screen. Having established that L_0 varies with screen position, it seemed possible that the weightings and γ may also vary. It was therefore considered necessary to characterise the screen at multiple screen locations.

Given that each batch of measurements needed to be collected within a 20 minute period to avoid the measurements spanning two meter re-calibrations, only a limited number of screen location and luminance level combinations could be measured. Given that the main use of the luminance response function was to enable a uniform screen luminance to be generated, it was considered important to characterise as many screen locations as possible, at the expense of the number of RGB levels if necessary. It was decided to measure only four RGB luminance levels, which would allow the screen to be characterised at 45 points in the time available. RGB levels of 0, 85, 170 and 255 were chosen as being reasonably equally spaced values that spanned the complete range of possible RGB levels. The 45 screen points to be characterised were arranged in an equally spaced 9 x 5 grid. Screen point 1 was at the top left corner of the screen, with the points incrementing from left to right, top to bottom.

6.1 Materials

The Apple M9179LL/A LCD was used as the display monitor. Twenty 320 x 320 pixel bitmap files were created in Matlab, four for calibration and the rest to display the chosen RGB levels at each colour. The RGB values of each file are shown in Table 4.

Table 4: RGB values of the bitmap files used to display the reference levels in each colour

	White	Red	Green	Blue
Calibration	50, 50, 50	50, 0, 0	0, 50, 0	0, 0, 50
RGB ₀	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0
RGB ₈₅	85, 85, 85	85, 0, 0	0, 85, 0	0, 0, 85
RGB ₁₇₀	170, 170, 170	170, 0, 0	0, 170, 0	0, 0, 170
RGB ₂₅₅	255, 255, 255	255, 0, 0	0, 255, 0	0, 0, 255

6.2 Procedure

The LCD was allowed to reach a stable operating temperature while displaying no image, i.e. RGB (0, 0, 0), over the entire screen. The calibration file was then displayed at the screen centre and its luminance was measured. The luminance of the RGB₀, RGB₈₅, RGB₁₇₀ and RGB₂₅₅ white files were then measured in turn at screen point 1. The average of 8 luminance readings was recorded for each file, with a two second delay between the presentation of a new file and the commencement of measurements to allow the luminance meter time to reach a stable reading at each RGB level. The luminance meter was then moved to screen position 2 where the measurements were repeated for each file.

The measurements continued at each screen point until all 45 had been measured, after which the luminance of the calibration file was again measured at the screen centre to determine the drift in measurements over the measurement period. The entire measurement process took approximately 18 minutes to complete. This procedure was repeated for the red, green and blue bitmap files. This procedure was first performed with the LCD backlight at minimum brightness, then at maximum brightness.

Once the measured luminance of each RGB level of each colour at all screen points were collected, the luminance response function curves could be calculated. At each point L_0 was calculated as the average of the four RGB₀ measures. Excel Solver was then used to determine the weighting and γ parameters of equation 1 that produced the lowest RMS error.

6.3 Results

6.3.1 Minimum Backlight Brightness

For each of the screen points measured, a curve that minimised the RMS error was fitted to the measured luminance at the four RGB levels. The curve was constrained to match the measured RGB level zero luminance. Figure 12 shows both the measured luminance and the fitted curve which minimised RMS error for the centre screen point. An inspection of

Figure 12 shows that the measured luminance of RGB level 85 fits well, but the measured luminance at RGB level 170 is above the fitted curve for all colours and the measured luminance at RGB level 255 is below the fitted curve for all colours. The error at RGB level 170 was 2.9% for white, 2.9% for red, 2.0% for green and 4.3% for blue. The error at RGB 255 was 2.0% for white, 2.7% for red, 1.4% for green and 3.5% for blue. This pattern was repeated for all screen points, suggesting a systematic error in the fit of the curve. It appeared that at higher RGB levels the relationship between RGB level and luminance may not follow the same relationship as it does at lower RGB levels.

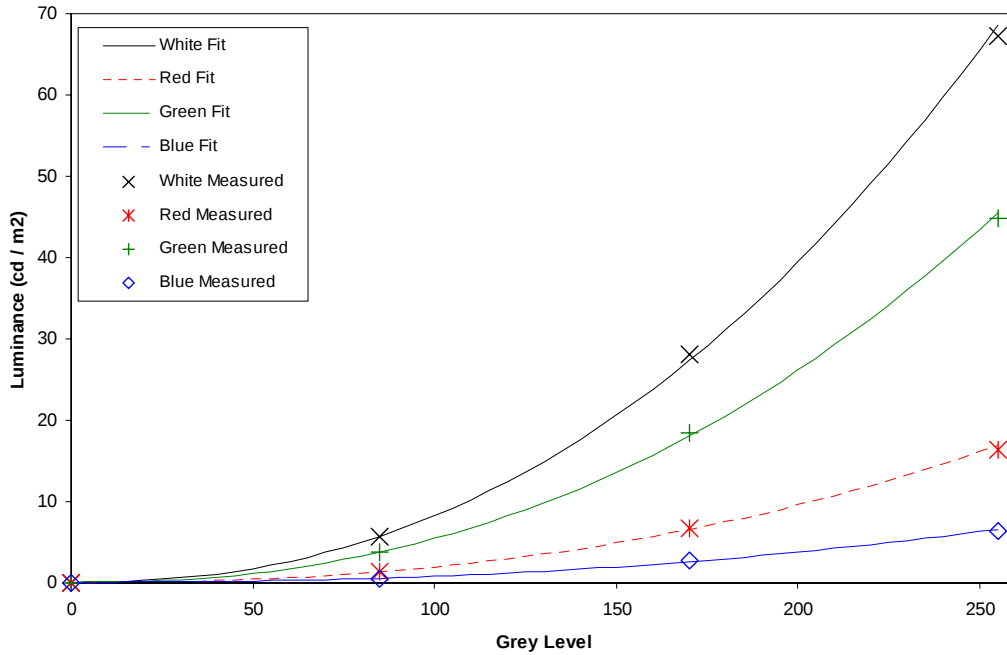


Figure 12: The markers show measured centre-screen luminance (cd/m^2) for RGB levels of 0, 85, 170 and 255 for white, red, green and blue colours at minimum LCD brightness. The lines show the best fitting form of Equation 1.

Although the discrepancy was not large, it was decided to use a two-stage curve to fit the measured points. A power function was used to fit RGB levels up to 170, and a linear function was used between RGB level 170 and RGB level 255. This is formalised in equation 2. The average values of the curve parameters and residuals over all screen points are shown in Table 5. The residuals at GL170 and GL255 using Equation 2 are substantially lower than the residuals obtained using Equation 1, which ranged between 2% and 4%.

$$L = L_0 + bI^\gamma \quad \text{for } 0 \leq RGB < 170,$$

$$L = L_0 + bL_{170}^\gamma + \left(\frac{L_{255} - L_{170}}{85} \right) (I - 170) \quad \text{for } 170 \leq RGB \leq 255. \quad (2)$$

Where	L	= Output Luminance
	L ₀	= Luminance at RGB Level 0
	L ₁₇₀	= Luminance at RGB Level 170
	L ₂₅₅	= Luminance at RGB Level 255
	b	= Constant
	I	= Input RGB Level
	γ	= Constant, often in the range 1.8 – 3.0

Table 5: Values of the fitted curve parameters, residuals and RMS error for minimum screen brightness averaged over 45 screen points. Standard deviations are in parenthesis.

	White	Red	Green	Blue
L0	0.098 (0.023)	0.098 (0.023)	0.098 (0.023)	0.098 (0.023)
b	0.00025 (0.00010)	0.00005 (0.00002)	0.00016 (0.00007)	0.00002 (0.00001)
γ	2.287 (0.062)	2.315 (0.056)	2.295 (0.067)	2.314 (0.055)
Residual at GL0	0.00% (0.00%)	0.00% (0.00%)	0.00% (0.00%)	0.00% (0.00%)
Residual at GL85	0.37% (0.43%)	-0.94% (1.48%)	1.77% (1.56%)	-2.66% (2.26%)
Residual at GL170	-0.01% (0.02%)	0.11% (0.17%)	-0.07% (0.07%)	0.33% (0.34%)
Residual at GL255	0.00% (0.00%)	0.00% (0.00%)	0.00% (0.00%)	0.00% (0.00%)
Average RMS Error	0.41% (0.39%)	1.04% (1.42%)	1.80% (1.52%)	2.79% (2.15%)

From Figure 12 it can be seen that appreciably different measured luminance levels are produced by each colour at equivalent RGB levels. Specifically, green produced 66%, red produced 24% and blue produced just 10% of the luminance produced by white. As the J17 luminance meter uses the same photopic curve as the human eye, this result suggests that the visibility of each colour will be noticeably different if displayed at equivalent RGB levels. This suggests that application software should correct for this by adjusting grey levels to provide equivalent visibility for all colours.

As a test of the accuracy of these luminance curves to produce expected luminance levels, the screen centre luminance of all colours was measured after using the luminance curves to calculate the RGB values to achieve luminance levels of 0.2 cd/m², 1.0 cd/m², 3.0 cd/m², 6.0 cd/m², 15.0 cd/m², 30.0 cd/m² and 60.0 cd/m². The average of 11 measurements taken at various times over a period of several days for each luminance level is shown in Table 6.

Table 6: Mean luminance and mean percentage error of 11 measurements of screen-centre luminance for white, red, green and blue over a range of expected luminance values

Target Luminance (cd / m ²)	Measured Luminance (cd / m ²)				Percentage Error			
	White	Red	Green	Blue	White	Red	Green	Blue
0.2	0.20				0.9%			
1.0	0.98				-2.4%			
3.0	2.59	3.04	2.90	2.91	-13.7%	1.4%	-3.4%	-3.1%
6.0	5.84	5.85	6.11	5.90	-2.7%	-2.5%	1.8%	-1.7%
15.0	14.84	14.53	14.65		-1.0%	-3.1%	-2.3%	
30.0	28.68		27.52		-4.4%		-8.3%	
60.0	57.66				-3.9%			

As can be seen from the above table, all the values are within 5% of the expected luminance except for white luminance level 3.0 cd/m², which was within 14% of the expected value. To overcome the high error seen in this condition, when a white luminance of 3.0 cd/m² was required, the calculated response curve was initially used to produce the bitmap file, whose RGB values were then scaled to achieve the required luminance.

6.3.2 Maximum Backlight Brightness

A similar exercise was conducted for the LCD when set to maximum brightness. Again the tendency of a single power function curve to underestimate the measured luminance at an RGB level of (170, 170, 170) and overestimate the measured luminance at an RGB level of (255, 255, 255) was noted. However, the magnitude of the errors were less at maximum brightness than those seen at minimum brightness and it was decided to use a power function to characterise the luminance response across all RGB levels. The values of the curve values and residuals for each colour at maximum brightness are shown in Table 7.

Table 7: Values of the fitted curve parameters, residuals and RMS error for maximum screen brightness averaged over 45 screen points. Standard deviations are in parenthesis.

	White	Red	Green	Blue
L0	0.652 (0.122)	0.652 (0.122)	0.652 (0.122)	0.652 (0.122)
b	0.00147 (0.00068)	0.00026 (0.00012)	0.00095 (0.00046)	0.00012 (0.00006)
γ	2.214 (0.085)	2.270 (0.086)	2.220 (0.086)	2.251 (0.088)
Residual at GL0	0.00% (0.00%)	0.00% (0.00%)	0.00% (0.00%)	0.00% (0.00%)
Residual at GL85	-1.18% (0.69%)	-0.99% (0.72%)	-1.00% (0.75%)	-1.40% (0.82%)
Residual at GL170	3.39% (1.98%)	2.96% (1.86%)	2.88% (2.11%)	4.10% (1.88%)
Residual at GL255	-2.00% (1.11%)	-1.81% (1.03%)	-1.71% (1.19%)	-2.43% (1.02%)
Average RMS Error	4.11% (2.37%)	3.61% (2.15%)	3.59% (2.40%)	4.99% (2.24%)

The ability of these luminance curves to produce expected luminance levels is shown in Table 8, which shows the average of 13 screen centre luminance measurements for all colours was measured for expected luminance levels of 1.0 cd/m², 15.0 cd/m², 25.0 cd/m², 60.0 cd/m², 150.0 cd/m² and 280.0 cd/m². All the mean errors are within 5% of expected values.

Table 8: Mean luminance and mean percentage error of 13 measurements of screen-centre luminance for white, red, green and blue over a range of expected luminance values

Target Luminance (cd / m ²)	Measured Luminance (cd / m ²)				Percentage Error			
	White	Red	Green	Blue	White	Red	Green	Blue
1.0	0.97				-3.4%			
15.0	15.25	15.09	14.79	15.34	1.7%	0.6%	-1.4%	2.3%
25.0	24.43	25.28	25.80	25.16	-2.3%	1.1%	3.2%	0.7%
60.0	60.44	59.94	61.04		0.7%	-0.1%	1.7%	
150.0	149.91		148.88		-0.1%		-0.7%	
280.0	276.35				-1.3%			

7. Verification of Luminance Characterisation

The previous results should allow a target luminance level to be displayed which, once the LCD had reached a stable operating temperature, should show little variation over the course of a day. This premise was tested for a range of display luminance levels.

7.1 Materials

The Apple M9179LL/A LCD was used as the display monitor and the Tectonics J17 luminance meter was used to measure the screen brightness.

Sixteen 300 x 300 pixel bitmap files were created as display tiles with the following target colour / luminance combinations:

White: 0.2 cd/m², 1.0 cd/m², 3.0 cd/m², 6.0 cd/m², 15.0 cd/m², 30.0 cd/m², 60.0 cd/m².
 Red: 3.0 cd/m², 6.0 cd/m², 15.0 cd/m².
 Green: 3.0 cd/m², 6.0 cd/m², 15.0 cd/m², 30.0 cd/m².
 Blue: 3.0 cd/m², 6.0 cd/m².

7.2 Procedure

After allowing the LCD to reach its stable operating temperature, each bitmap file was displayed sequentially at the screen-centre for a period that allowed an average of 15 luminance readings to be recorded. The measurements were taken at various times over a period of several days at both minimum and maximum backlight settings.

7.3 Results

7.3.1 Minimum Screen Brightness

The mean percentage error and range of percentage error of the luminance readings with the LCD set to minimum brightness are shown in Table 9.

Table 9: Mean percentage error and range of percentage error of 11 measurements of screen-centre luminance for white, red, green and blue over a range of expected luminance values

Target Luminance (cd / m ²)	Mean Percentage Error				Range of Error ($\pm$ Mean)			
	White	Red	Green	Blue	White	Red	Green	Blue
0.2	2.2%				1.4%			
1.0	-2.4%				3.5%			
3.0	-13.7%	1.4%	-3.4%	-3.1%	1.2%	1.1%	1.0%	0.9%
6.0	-2.7%	-2.5%	1.8%	-1.7%	0.7%	0.7%	0.5%	0.3%
15.0	-1.0%	-3.1%	-2.3%		0.3%	0.3%	0.2%	
30.0	-4.4%		-8.3%		0.2%		0.1%	
60.0	-3.9%				0.1%			

7.3.2 Maximum Screen Brightness

The mean percentage error and range of percentage error of the luminance readings with the LCD set to maximum brightness are shown in Table 10.

Table 10: Mean percentage error and range of percentage error of 13 measurements of screen-centre luminance for white, red, green and blue over a range of expected luminance values

Target Luminance (cd / m ²)	Mean Percentage Error				Range of Error ($\pm$ Mean)			
	White	Red	Green	Blue	White	Red	Green	Blue
1.0	-3.4%				2.1%			
15.0	1.7%	0.6%	-1.4%	2.3%	0.7%	1.3%	1.8%	0.9%
25.0	-2.3%	1.1%	3.2%	0.7%	1.7%	2.0%	1.8%	0.6%
60.0	0.7%	-0.1%	1.7%		1.6%	1.7%	1.6%	
150.0	-0.1%		-0.7%		1.6%		1.2%	
280.0	-1.3%				1.1%			

As can be seen from the above tables, with the exception of white with a luminance of 3.0 cd/m², the method used to produce specific luminance levels produced results that were within 4% of the target. For all conditions luminance varied by less than $\pm 4\%$ around the mean. It was unclear why the white 3.0 cd/m² condition had a relatively high mean error, but as the variation was in line with the other conditions, the obtained RGB values were manually scaled to achieve a measured luminance of 3.0 cd/m².

This requirement to manually scale, combined with the result that the percentage error obtained using the characterisation procedure is not a substantial improvement over the initially observed errors, indicates that the characterisation methods were not satisfactory. It seems likely that the limited number of data points used to characterise the luminance response function was a major factor in this result, particularly given that the assumption that the response function would be constant over the entire RGB range may be untenable for LCDs (TG18, 2005). A better approach, given the performance constraints of the luminance meter, would to have been to determine the RGB levels necessary to achieve the specific luminance levels required at each screen location, rather than attempting to determine a general classification curve.

8. LCD Luminance Uniformity Correction

Having determined the luminance response curve of each measured screen point, it was possible to calculate the RGB level needed at each measured point to achieve a particular luminance level and then interpolate between the measured points to determine what the RGB level of each screen pixel needed to be to produce a bitmap file that achieves a uniform luminance level across the screen.

8.1 Materials

The luminance response curves obtained at each screen point were used as the basis of the analysis performed in Excel and Matlab.

8.2 Procedure

The luminance response curves were used to calculate the RGB level required at each measured screen point to achieve a required luminance level for white, red, green and blue. The pixel coordinates and the required RGB level of each of the 45 measured screen points were used as an input to Matlab. The INTERP3 function with a linear interpolation method was used to generate a 1600×2560 matrix where each entry was the RGB level of a pixel predicted to achieve the required luminance at that screen position. This matrix was converted into a bitmap file that aimed to produce a constant screen luminance.

This method produced an output file in which the RGB level contours were visually apparent. To reduce this undesirable effect a nonlinear filter was applied to a 50×50 pixel sliding window, which replaced the centre pixel with a pixel randomly selected from within the window. This was successful in producing a display with no visually apparent contours.

8.3 Results

8.3.1 Minimum Screen Brightness

Tests were performed to determine how accurately uniform background luminance levels of 0.2 cd/m^2 and 1.0 cd/m^2 could be created. These levels were the lowest uniform luminance values that could be achieved at minimum and maximum backlight brightness respectively. These tests involved measuring the luminance at 40 screen points at different screen positions to those used to produce the uniformity calculations. For the expected luminance of 0.2 cd/m^2 the mean luminance across all the measured points was $0.21 \text{ cd/m}^2 \pm 17\%$. For the expected luminance of 1.0 cd/m^2 the mean luminance across all 40 measured points was $0.98 \text{ cd/m}^2 \pm 6\%$.

These results can be compared to the uncorrected luminance variation. This was approximately $\pm 30\%$ about the mean for a luminance of 0.2 cd/m^2 , and thus the correction approximately halved the variation in luminance. For a luminance of 1.0 cd/m^2 , the

uncorrected luminance variation and ranged from 20% below the mean to 34% above the mean, which the correction reduced to $\pm 6\%$.

8.3.2 Maximum Screen Brightness

With the LCD set at maximum brightness and an expected luminance of 1.0 cd/m^2 , the measured mean luminance over the 40 screen points was $0.93 \text{ cd/m}^2 \pm 14\%$. Again this can be compared to the uncorrected luminance variation, which ranged from 19% below the mean to 33% above the mean. Thus the range of variance was reduced from 52% to 28%, again approximately halving the variation in luminance.

In each case, a substantial improvement in luminance uniformity was obtained. However, this leaves open the question of whether this improvement was sufficient. The reason for attempting to improve the luminance uniformity was to reduce the uncertainty about the level of luminance adaptation. This aim does not lead itself to an obvious criterion, but guidance can possibly be taken from applications in which luminance characteristics are critical. Medical imaging is an area that requires displays to exhibit highly uniform luminance in order to correctly interpret the results of various scans. The American Association of Physicists in Medicine set up the AAPM Task Group 18 to establish standards for medical displays, and this group recommended that luminance variation should be less than 30% (TG18, 2008). The corrected luminance uniformity met this standard in two of the three conditions, and was only 2% over the recommendation in the worst condition.

9. Luminance of Different Sized Characters

The previous measurements relating luminance to RGB level were all performed on large contiguous pixel blocks of constant RGB level. However, in order to enhance the perceived image sharpness, LCDs may adjust luminance levels at the boundary of a luminance transition. Thus the pixel luminance of a small character, such as a letter with a stroke width of one or two pixels, may differ from that of a solid block of contiguous pixels even if both have the same RGB level. This section identifies whether the per-pixel luminance of large and small characters with the same RGB value are equivalent.

This was tested by measuring whether the luminance of a fixed number of pixels of a particular RGB level depended on whether the pixels were arranged in a solid block or in a checkerboard pattern. If the luminance depended on the pattern of pixels, this would suggest that the luminance response function results obtained previously for large blocks of pixels could not be used to predict the luminance of small characters. However, if the luminance did not depend on the pattern of pixels, the previous luminance response results could be used with confidence to predict the luminance of small characters. As an additional test, the luminance of the letter "R" displayed at a range of font sizes was measured. The number of pixels of each letter size was identified, and the luminance of the letter was compared with the solid and checkerboard patterns with equivalent pixels

counts. Identical luminance levels would establish that the checkerboard results could be applied to real letters.

9.1 Materials

The Apple M9179LL/A LCD was used as the display monitor and the Tektonix J17 luminance meter was used to measure screen brightness. The LCD was set to minimum brightness.

Twenty 600 × 600 pixel bitmap files were created with a background RGB level of (20, 20, 20), and with 0, 4, 20, 52, 100, 164, 244, 340, 452 and 508 pixels with an RGB value of (125, 125, 125). The bright pixels were either arranged as a solid block or in a checkerboard pattern. Six bitmap files of the capital “R” rendered in Verdana font were created with pixel heights of 10, 13, 16, 20, 25 and 32. These letters were also created with an RGB level of (125, 125, 125) over a background RGB level of (20, 20, 20) and contained 25, 71, 89, 144, 207 and 340 bright pixels respectively. Font smoothing was disabled. The bright RGB level of 125 was chosen to be in the middle of the possible range, and a background of (20, 20, 20) was chosen instead of (0, 0, 0) in order to explore whether pixels adjacent to bright pixels were reduced in luminance to enhance edge sharpness. This type of luminance reduction would have been masked if the background pixels had been set to zero.

9.2 Procedure

Measurements were taken several hours after the LCD was switched on in order for it to achieve a stable operating temperature. The bitmap files were displayed sequentially and the luminance level was visually determined from the J17 display. All measurements were taken within a 20 minute period to avoid any effects of meter recalibration.

9.3 Results

The measured luminance of each stimulus is shown in Figure 13. An inspection of Figure 13 reveals that the measured luminance of a particular number of pixels was the same irrespective of whether the pixels were arranged in a solid block, a checkerboard pattern or the letter “R”. This indicates that for the software configuration of the LCD used in the study, the previously determined luminance response curves can be applied to predict the luminance of small characters. However, if display features such as ClearType™ were applied, this result may not continue to hold because font smoothing may cause luminance to be non-uniform across characters.

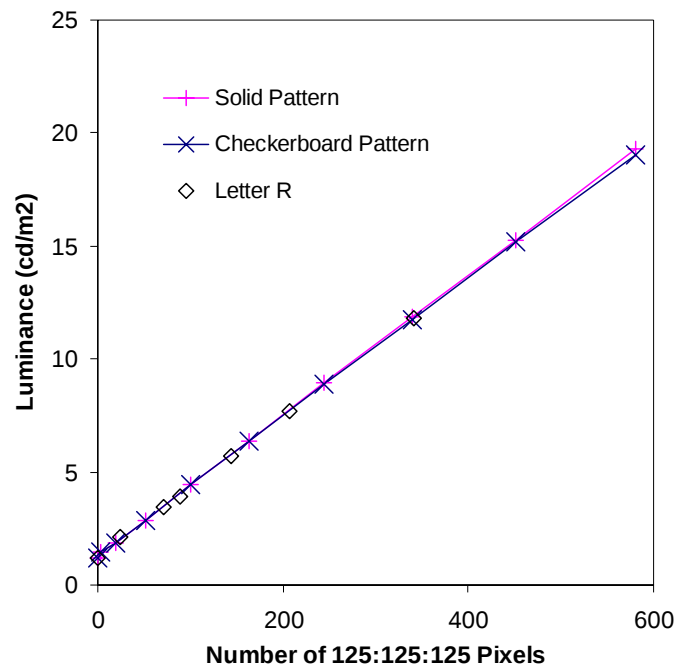


Figure 13: The measured luminance of 600 x 600 pixel bitmap files with a background RGB level of (20, 20, 20) and with various numbers of pixels with an RGB level of (125, 125, 125) arranged in a solid block, a checkerboard pattern or capital "R"

10. Summary

The reason for taking the measurements outlined above was to develop an understanding of the LCD screen characteristics that would enable the display of visual stimuli at specific luminance levels over a background of uniform luminance for a specific duration, within known error limits. To this end, measures of the uncorrected screen luminance uniformity were taken, as well as measures of the stability of luminance over time, the stability of luminance after step changes in display RGB level, the spectral characteristics of the display, the display luminance response and the rise time of the LCD. These measures allowed the display uniformity to be improved and allowed an estimate of the potential variance in luminance that could be expected over a one-day period.

The initial measurement taken was the uncorrected screen luminance uniformity because if the screen was sufficiently uniform, no correction would be necessary. However, luminance was found to vary between $\pm 30\%$ of mean luminance. This range of variation was considered unacceptable.

In addition to being non-uniform, the screen luminance of the Apple LCD was found to be influenced by several factors. One of these was temperature, with the screen luminance increasing by almost 50% during a 1.5 hour warm-up period. After reaching a stable operating temperature, the ambient air temperature also appeared to affect the LCD

luminance, but to a far lesser extent, with variations of between 3% and 4% being observed over the course of a working day in an air-conditioned laboratory environment. Thus from about 1.5 hours after switch-on, the normal temperature variations found in air-conditioned environments did not have a large effect on the luminance.

The LCD also took time to completely stabilise its luminance after a change in display RGB level, with the measured luminance increasing by 2% over a 1.5 hour period after a change from RGB level 0 to RGB level 255. However, this effect was considered to be insignificant in the proposed experimental application, as high RGB levels will only be displayed for 2 seconds or less before being removed.

Having determined that the screen luminance will be largely stable after allowing for an initial warm-up period of approximately 1.5 hours, the luminance response function of white, red, green and blue was measured at 45 screen points, and a response curve fitted at each screen point for each colour and minimum and maximum backlight brightness settings. The response curve varied widely between the colours, with blue producing only 10% of the luminance of white at the same RGB level. The accuracy of the response curves was tested by measuring screen-centre luminance of white, red, green and blue for expected luminance levels ranging from 0.2 cd/m² to 280 cd/m². At the minimum brightness setting, all but two measured readings were within 10% of the expected values. At the maximum brightness setting, all but one measurement were within 10% of the expected value.

The fitted response curves allowed the calculation of the RGB level at each measured screen point to achieve a desired luminance. Linear interpolation was used to calculate the necessary RGB level at each pixel, which allowed for a bitmap file to be produced to increase the uniformity of the luminance compared to a constant RGB level display. To validate the process, the luminance uniformity of the bitmap files was measured for expected luminance levels of 0.2 cd/m² and 1.0 cd/m² at the minimum backlight brightness setting and 1.0 cd/m² for the maximum backlight brightness setting. At the minimum backlight brightness, the mean measured luminance was 0.21 cd/m² $\pm$ 17% for an expected luminance of 0.2 cd/m². This compared to an uncorrected luminance variation $\pm$ 30%. For an expected luminance of 1.0 cd/m², the measured mean luminance was 0.98 cd/m² $\pm$ 6%, which can be compared with the uncorrected luminance range from 20% below to 34% above the mean. At the maximum backlight brightness, the mean measured luminance was 0.93 cd/m² $\pm$ 14% for an expected luminance of 1.0 cd/m², compared to an uncorrected luminance ranging from 19% below to 33% above the mean.

Finally, measurements of seven expected luminance levels at screen-centre were taken a number of times over the course of several days to provide an estimate of the expected daily variation in luminance levels. For expected luminance levels of 0.2 cd/m² and 1.0 cd/m², the measured luminance varied by less than $\pm$ 8% around the mean. For the higher five expected luminance levels, the measured luminance varied by less than $\pm$ 3% around the mean.

The finite rise and fall times of the LCD meant that the period for which the luminance of a stimulus was within 25% of its maximum value was between 10 – 12 ms less than the

nominal display duration. The exact value the difference depended on the luminance level. The 'on' time of a stimulus was able to be controlled in integer steps of video frame periods.

11. Conclusions

- The uncorrected level of variance in the luminance across the Apple M9179LL/A 30" LCD was approximately $\pm 30\%$ when displaying a constant RGB level. Based on a characterisation of the LCD luminance response function, the RGB levels necessary at each pixel to achieve a uniform luminance were calculated. Displaying a bitmap file containing these corrected RGB levels produced variations in luminance ranging from $\pm 6\%$ to $\pm 17\%$, depending on the expected luminance level.
- Using the characterised luminance response function, luminance levels could be generated that were generally within 5% of the expected levels at screen centre.
- The pixel luminance of stimuli did not vary with stimulus size.
- LCD luminance could increase by up to 50% during the warm-up period, but once warm the LCD showed a variation of less than $\pm 4\%$ over the course of a working day.
- The time that a display is within 25% of its maximum value is between 10 – 12 ms less than the nominal display period, with the exact difference dependent on the specific luminance levels.
- The relative luminance of the red, green and blue display colours is not equal. In particular, the blue response for a particular RGB value is particularly low in luminance compared to red and green. This suggests that equating RGB values is not a sound basis for displaying colours. It also suggests that pure blue may need to be avoided in any display implementation.

12. References

- CIE. (1995). *CIE 116-1995 Industrial Colour-Difference Evaluation*: Commission Internationale De L'Eclairage.
- Fletcher, K. I., Sutherland, S. J., & Nugent, K. (2009). *Identification of Text and Symbols on an LCD Part II: Contrast and Luminance Settings to Optimise Legibility* (No. DSTO-TR-2144). Adelaide: Defence Science and Technology Organisation.
- Fletcher, K. I., Sutherland, S. J., Nugent, K., & Grech, M. (2009). *Identification of Text and Symbols on an LCD Part III: The Effect of Ambient Light, Colour and Size* (No. DSTO-RR-0332). Adelaide: Defence Science and Technology Organisation.
- ITU. (1990). *Recommendation ITU-R Bt.709, Basic Parameter Values for the HDTV Standard for the Studio and for International Programme Exchange*. Geneva: ITU.
- Montag, E. D., & Berns, R. S. (1999). Visual Determination of Hue Suprathreshold Color-Difference Tolerances Using CRT-Generated Stimuli. *Color Research and Application*, 24(3), 164-176.
- TG18, A. (2005). *AAPM On-Line Report No. 03. Assessment of Display Performance for Medical Imaging Systems*. College Park, MD: American Association of Physics in Medicine.
- TG18, A. (2008). Assessment of Display Performance for Medical Imaging Systems: Executive Summary of AAPM TG18 Report. *Medical Physics*, 32(4), 1205-1225.

Appendix A: Equipment Technical Specifications

An Apple M9179LL/A 30" LCD monitor with a native resolution of 2560 x 1600 pixels at 60 Hz was used to display all stimuli. This was driven by a Hewlett Packard desktop computer with a P4, 3.6 GHz processor, 1 Gb of RAM and a NVIDIA GeForce 7800 GTX 256 MB dual-link DVI video card capable of driving the LCD at its native resolution.

The system software was Windows XP with the ClearType feature disabled in order to eliminate possible stimulus luminance non-uniformity caused by font-smoothing and anti-aliasing. Custom software was written to control the stimulus presentation using Java RE 6.0 and PXLab 2.1.6.

A chin and forehead rest was used to maintain a constant viewing distance from the screen. A Tectronix J17 photometer with a J1803 luminance sensor head was used to collect luminance measurements.

An Ocean Optics S2000 Spectrometer was used to measure spectral density from which CIE colour coordinates were calculated.

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION DOCUMENT CONTROL DATA					
				1. PRIVACY MARKING / CAVEAT (OF DOCUMENT)	
2. TITLE Identification of Text and Symbols on a Liquid Crystal Display Part I: Characterisation of the Luminance, Temporal and Spectral Characteristics			3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)		
4. AUTHOR(S) Kingsley Fletcher and Stuart Sutherland			5. CORPORATE AUTHOR DSTO Defence Science and Technology Organisation PO Box 1500 Edinburgh South Australia 5111 Australia		
6a. DSTO NUMBER DSTO-TN-0770		6b. AR NUMBER AR-013-964		6c. TYPE OF REPORT Technical Note	
7. DOCUMENT DATE February 2009					
8. FILE NUMBER 2008 / 1038898 / 1		9. TASK NUMBER NAV 07 / 094		10. TASK SPONSOR COMAUSNAVSURFGRP	
				11. NO. OF PAGES 29	
				12. NO. OF REFERENCES 7	
13. URL on the World Wide Web http://www.dsto.defence.gov.au/corporate/reports/DSTO-TN-0770.pdf			14. RELEASE AUTHORITY Chief, Maritime Operations Division		
15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT <i>Approved for public release</i>					
OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, EDINBURGH, SA 5111					
16. DELIBERATE ANNOUNCEMENT No Limitations					
17. CITATION IN OTHER DOCUMENTS Yes					
18. DSTO RESEARCH LIBRARY THESAURUS http://web-vic.dsto.defence.gov.au/workareas/library/resources/dsto_thesaurus.shtml Liquid crystal displays, naval displays, visual acuity, data visualisation, image identification, human factors engineering					
19. ABSTRACT This report outlines the measurements performed on an Apple M9179LL / A 30' 2560 x 1600 LCD panel to establish its luminance response function, luminance uniformity, luminance temporal stability, response time and spectral characteristics. The results of this report were used in subsequent reports (Fletcher, Sutherland, & Nugent, in press; Fletcher, Sutherland, Nugent, & Grech, in press) which examined the minimum character size that allowed for fast and accurate identification of numbers, letters and combat symbology under ambient lighting conditions experienced in naval operations rooms.					