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Limitations of visual gamma corrections in LCD displays

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A method for estimating the non-linear gamma transfer function of liquid–crystal displays (LCDs) without the need of a photometric measurement device was described by Xiao et al. (2011) [1]. It relies on observer's judgments of visual luminance by presenting eight half-tone patterns with luminances from 1/9 to 8/9 of the maximum value of each colour channel. These half-tone patterns were distributed over the screen both over the vertical and horizontal viewing axes. We conducted a series of photometric and psychophysical measurements (consisting in the simultaneous presentation of half-tone patterns in each trial) to evaluate whether the angular dependency of the light generated by three different LCD technologies would bias the results of these gamma transfer function estimations. Our results show that there are significant differences between the gamma transfer functions measured and produced by observers at different viewing angles. We suggest appropriate modifications to the Xiao et al. paradigm to counterbalance these artefacts which also have the advantage of shortening the amount of time spent in collecting the psychophysical measurements.

1. Introduction

Liquid–crystal displays (LCDs) are the dominant technology for displaying visual information nowadays. They have become so due to their relative inexpensiveness, low power consumption and convenient screen-size to total-volume ratios. In consequence, LCDs are available at increasingly larger sizes, with image quality characteristics (e.g. colour gamut maximum luminance, contrast ratio and spatial resolution) that usually exceed those of the formerly dominant *cathode-ray tube* (CRT) technology [2].

However, with the increasing popularization of LDC technologies there is also an increased need for more accurate colour management. For this reason, *display characterization* [3] is an essential step for accurately controlling the colour of displayed images. In this regard, CRT monitor technology has been extensively studied in the past both in terms of their colour characteristics [4,5] and calibration techniques [6,7], including those that rely on visual comparison instead of a photometer [8]. On the other hand, corresponding LCD colour characteristics and calibration methods have started to be reported much later [1,2,9].

The characterization of a display usually involves two stages [4]: (a) modelling the non-linear relationship between the electrical signals used to drive the display and the radiant output produced by each of the display's chromatic channels, and (b) modelling the linear transformation that converts the device-dependent RGB output to a device-independent tristimulus space (e.g. CIEXYZ). The relationship described in (a) is termed the *opto-electronic transfer function* (OETF). In the case of CRT monitors, the OETF is usually determined by the physics of the display and can be modelled as a power function with an exponent commonly labelled "gamma" (and hence the function is sometimes called the "gamma" function) [6,7]. In the case of LCD displays the OETF is much more difficult to determine, in part because of the more complex physics and in part because of the tendency for manufacturers to account for suboptimal voltage-lightness relationships by remapping it via look-up tables [2]. In addition, backwards-compatibility issues constrain LCD manufacturers to mimic the performance of older CRT displays, regardless of the physical differences between both technologies.

The main problems hampering the performance of LCD monitors and introducing noise in the determination of their OETF are [10]: (a) leakage of light in the OFF state of an LCD, (b) colour and brightness variations as a function of viewing angle and ambient light (c) OEFT dependency on material and cell structure parameters (d) measurement errors introduced by instruments sensitive to light polarization (e) chromaticity variations with

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luminance (light leakage) (f) cross-talks between neighbouring pixels (g) dependency of display characteristics with temperature (h) need for measurement instruments to capture the narrow-band fluorescent lights used as LCD light sources (i) complex reflection of ambient light from the display screen.

1.1. LCD technology

Fig. 1 shows the schematics of a pixel element inside one of the most common LCD types, the backlit *Twisted Nematic* (TN) LCD [11–13]. The light is usually produced by LEDs or fluorescent elements and a mosaic of R, G and B filters is aligned to the substrate glass producing coloured cells that are controlled independently, so that the human visual system integrates their light in the same way as it does for CRT monitors. For this reason, most CRT colour models hold for LCDs if we assume the same sort of channel independence [9]. However, the OETF of an LCD pixel cell tends to be a sigmoid (S-shaped) function, which is quite different from the usual "gamma" power function of CRT monitors. To allow for backwards compatibility, LCD monitors share some of the characteristics of CRTs such as R, G and B chromaticities and inbuilt tone-response compensations to mimic the power-law relations present in CRTs.

TN displays suffer heavily from the unintended activation of non-addressed pixels (crosstalk) and need some kind of additional non-linear electronic elements into each pixel cell, e.g. thin-film diodes, or transistors applied to individual picture elements in order to avoid it. There is also a well-known dependency of the OETF of individual cells with viewing angle [2].

Another popular LCD technology is termed *Vertical Alignment* (VA) [14–17]. The main difference with TN technology is that when no voltage is applied, the liquid crystals do not allow the passage of light through the crossed polarisers (see Fig. 1). Given that their natural state is to block light, VA monitors provide good black depth. The OETF is again dependent on the viewing angle, but there is no reason for its dependency to be the same from that of TN displays.

A third popular LCD technology is called "*In-Plane Switching*" (IPS) [18,19]. It was invented in the 1970s and applied to large LCD panels in the 1990s as a way to improve on the poor viewing angle and the poor colour reproduction of TN panels. It owns its name to its main difference from TN panels: the electric field is applied parallel to the panel plane instead of perpendicular to it. In this arrangement, crystal molecules are aligned parallel to the panels in the ON state, reducing the amount of light scattering in the matrix, which arguably gives IPS much better wide viewing angles and good colour reproduction.

1.2. Perceptual gamma correction methods

The precise modelling of the OETF is likely to require a photometer with the corresponding cost and relatively higher degree of user expertise. However, a simpler (and cheaper) "perceptual" alternative has been developed and successfully used in CRT [8,20,21] and LCD [1,22] characterization, and in the case of CRT displays, there are several commercial gamma correction software available, e.g. Adobe Gamma (Adobe San Jose CA, US) and EasyRGB (http://EasyRGB.com).

These "perceptual" gamma correction methods require an observer to match a typical half tone pattern (composed by pixels either "black" or at peak value so that their average luminance is a known fraction the maximum luminance) to a uniform luminance patch. The paradigm relies on a perceptual illusion: that these small halftone pixels are blended into smooth tones by the human vision system. If we assume that the OETF is well described by a power function (as is the case in CRT monitors) we need only one mid-tone measurement per chromatic channel to model it. However, given the more complex nature of LCD displays, observer variability and the factors mentioned above, more "half-tone" pattern matches are typically needed to model LCD displays. In the particular method devised by Xiao et al. [1] eight different halftone patches were used to generate the data points needed for modelling the OETF in each chromatic channel. These patches (3×3 pixel blocks) were set to average luminances equal to 1/9, 2/9, 3/9, 4/9, 5/9, 6/9, 7/9 and 8/9 of the maximum display

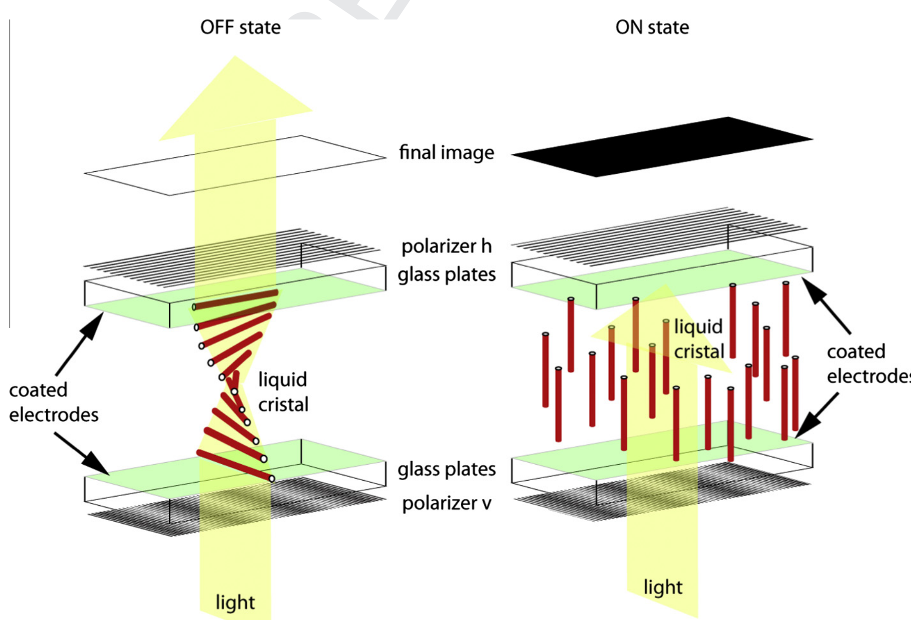

Fig. 1. Schematics of a Twisted Nematic (TN) pixel element (cell). The left part of the figure represents the cell's OFF state, where no voltage is applied to the electrodes allowing the light from the light source (e.g. LED backlighting or cold cathode fluorescent backlighting) to arrive to the observer's eye. The right part of the screen represents the ON state, where a voltage is applied to the electrodes resulting in most of the light to be blocked by the two orthogonally oriented polarisers.

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luminance. Observers were asked to match the luminance of a uniform disk to the overall luminance of a surrounding area, rendered from one of the half-tone patches. The results of these matches determined the shape of the fitted OETF.

1.3. Issues regarding the design of the experimental interface

In the experiment described by Xiao et al. [1] the user interface contained a single circular patch embedded in a half-tone rectangular background (see their Fig. 3) and observers manipulate the luminance of the circular patch by sliding a bar at the bottom of the rectangular background. To complete a single experiment, observers had to perform at least 24 successive matches. In a second (unpublished) version of their paradigm, eight combinations of haft-tone and uniform backgrounds were presented simultaneously in a 4×2 horizontal array, substantially accelerating the data gathering process by reducing the number of sequential screens that observers had to go through (see Fig. 2). Although this new experimental interface was better in terms of user satisfaction and speed, it presented a new challenge: here observers have to perform the same matching task, viewing the screen in directions other than perpendicular for patches away from the centre. Given the LCD displays' intrinsic artefacts, we ask ourselves whether the added noise imposed to the display would invalidate the results of such an experiment.

In particular, we ask the following questions:

(a) Is it possible to measure the shape of the OETF using a method similar to that described by Xiao et al. [1] with the stimuli distribution shown in Fig. 2?
(b) Are the answers to the previous questions equally valid for the three LCD technologies mentioned above? Which one is less prone to measurements artefacts for this same experimental set-up?

2. Material and methods

We answered the questions above by performing a set of complementary measures and psychophysical experiments. The measurements were aimed at describing the physics of angular viewing and whether this would influence the performance of human observers in doing the tasks described by Xiao et al.

2.1. Radiometric and colorimetric properties of LCD screens

We determined the properties of the four LCD screens in Table 1 at different viewing angles and viewing directions (perpendicular, top, bottom, left and right) by performing a set of colorimetric and radiometric measures. The makes and models in Table 1 were selected to include at least one representative for the three technologies described in the previous section. We measured spectral radiance, chromaticity and luminance (Y) using a Spectrascan PR650 spectroradiometer (SR) sold by Photo Research, Inc from Chatsworth, CA, US. Our measurements were conducted by displaying a series of 108 intensity levels ranging from 0 to the maximum luminance available. Since we did not want to test for screen uniformity or spatial independence, we always measured the same area at the centre of the screen, regardless of viewing angle. To perform our measures, we configured the LCD screen and the SR as shown in Fig. 3, measuring angles relative to the perpendicular position ($\alpha = 0$). For angular viewing, the SR was kept still while the screen was tilted a small angle.

The PR650 retrieved spectral and CIEXYZ [23] colorimetric data from solid patches in the 0–255 grey-level interval and from half-tone patches. The later were produced by a combination of on-and-off maximum intensity pixels. These pixel combination were referred by the number of "bright" pixels in a 3 by 3 array, that is, 1, 2, 3, . . ., 8 (see Fig. 2). All measurements were conducted on the three R, G, B channels separately and their achromatic

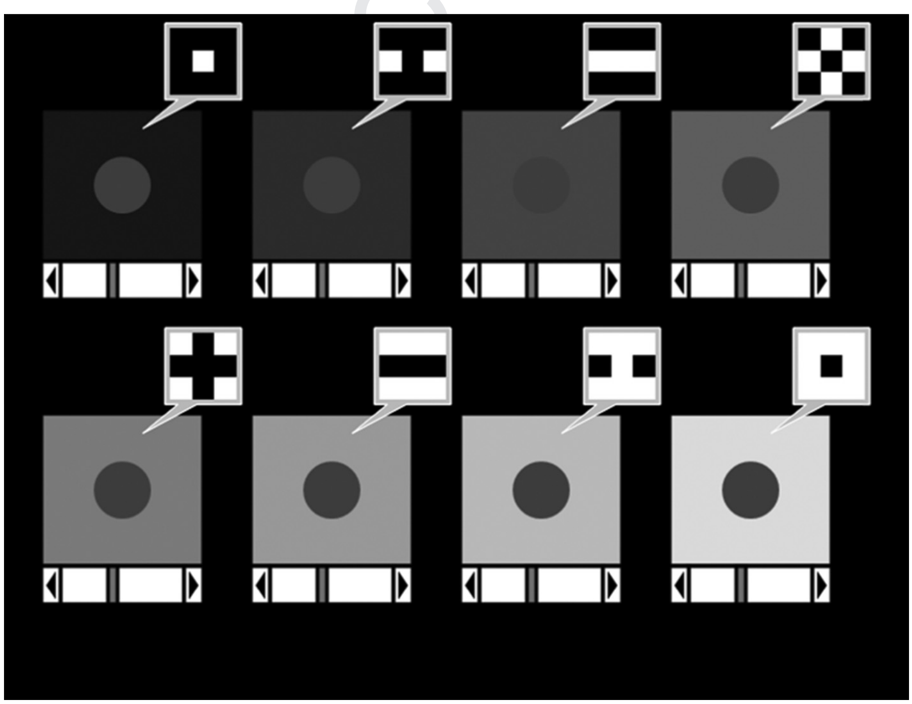

Fig. 2. Schematics of the new experimental interface designed to accelerate the data gathering process. Eight matching experiments can be performed at once. In each experiment, the observer has to match the circle to its surrounding "half-tone" background by sliding the bar at the bottom of each square. The callouts in the picture show how each half-tone pattern was produced by interleaving maximum-luminance and black pixels to produce the square backgrounds. Callouts are included in the figure for illustrative purposes only and were not present in the actual experiment. The same experiment was reproduced for each of the three R, G, B monitor colours separately. The matching squares were distributed over the entire extension of the screen.

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Table 1
Makes and models and their corresponding PC setup, LCD technology and screen size for the four displays tested. Different computers were used to avoid delays in connecting and disconnecting the screens. An extra LCD screen (Toshiba Tecra M9 laptop) was added to include another LCD technology (thin-film-transistor or TFT-LCD) in our tests [25].

Make and model	PC and OS details	LCD technology	Resolution (pics)
ASUS VH222D	DELL Precision 390 – Intel(R) Core(TM) Duo CPU 6600, 2.40 GHz, Windows XP Professional	Twisted Nematic (TN)	1920 × 1080
LG IPS231P	DELL Precision 390 – Intel(R) Core(TM) Duo CPU 6600, 2.40 GHz, Windows XP Professional	In-Plane Switching (IPS)	1920 × 1080
HP LE1711	DELL Precision 390 – Intel(R) Core(TM) Duo CPU 6600, 2.40 GHz, Windows XP Professional	Twisted Nematic (TN)	1920 × 1080
BenQ EW2730V	HP Compaq dc5800 Microtower PC, Intel(R) Core(TM) Duo CPU E8400, 3.00 GHz, Windows Vista Home	Vertical Alignment (VA)	1920 × 1080
Toshiba Tecra M9 (laptop)	Intel(R) Core(TM) Duo CPU T7500, 2.20 GHz, Windows XP Professional	Thin-Film-Transistor (TFT)	1440 × 900

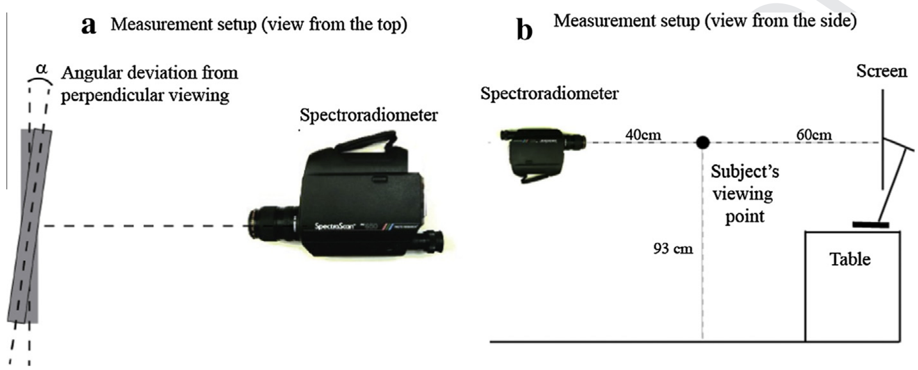

Fig. 3. Panel a shows the measurement set up between the screen and the spectroradiometer, viewed from the top. To perform off-axis measures, we rotated the screen an angle α instead of moving the instrument. Panel b shows the position of the SR with respect to the subject's head position. We visually checked that for both, subject and spectroradiometer, pixels were blended together.

combination (grey patches, termed "W") as well. All screen parameters (brightness, contrast, chromatic settings, etc.) were set to their factory default and CIELab calculations were based on the spectral power distribution of the display's white point and the CIE1931 2° standard observer [23]. The LCD screens were always driven by 24-bit display adapters with 8 bits for the R, G, and B channels. All equipment was warmed up for at least 60 min and measurement devices were calibrated as necessary. All experiments and measures were conducted within a period of 2 months. All psychophysical stimuli were programmed in Psychotoolbox [24] and OpenGL running in Matlab.

2.2. Controlled viewing conditions psychophysical experiments

Controlled viewing experiments were conducted on subjects using the ASUS VH222D LCD monitor run by a DELL Precision 390 PC driving an NVIDIA Quadro FX3450/4000 SDI graphics card. The experimental room was completely dark apart from the light coming from the test LCD screen. Subjects viewed the screen with their heads restrained by a chin-rest. They were always instructed to control and visually match the brightness of a uniform disk (2° of visual angle) to the (fixed) overall brightness of the surrounding area (6° by 6° of visual angle) which consisted of a half-tone pattern like those of Fig. 2. Only one match was allowed per pattern. While the spatial distribution of the patterns changed, the basic instructions were always the same. There were two viewing conditions: Experiment 1 (parallel matching) and Experiment 2 (serial matching). Ten subjects participated in Experiment 1 while nine of those participated in Experiment 2. They were all recruited from the local academic population (lecturers, postdoctoral students and two of the authors) and paid per hour. All subjects were tested for normal colour vision using the Ishihara and the Farnsworth Dichotomous (D-15) tests. They all had normal or corrected to normal visual acuity. We tested the monitor's uniformity by measuring luminance in the regions relevant to our experiment and we found an average variation of less than 4%.

Table 2
A list of the angles (first column) and directions (second column) from which the spectroradiometer was pointed at the central patch (see Fig. 3) in our colorimetric measures. The last column shows the denominations that we use for each of these in our plots.

Angle (degrees)	Direction	Denomination
0	Perpendicular	P
5	Upwards	5U
−5	Downwards	5D
9	Upwards	9U
−9	Downwards	9D
8	Right	8R
−8	Left	8L
22	Right	22R
−22	Left	22L

2.2.1. Experiment 1 (parallel matching)

Experiment 1 was designed to replicate that of Xiao et al. [1], therefore the geometry of the pattern was similar with all patterns presented at the same time. Observers viewed the screen from 60 cm distance with their eyes levelled with the centre and their heads restrained by a chin rest. The luminance of the disks was controlled using a horizontal bar located at the bottom of each matching pattern. There were 8 rectangular stimuli to match in each condition, four located on the top row and four located on the bottom row which were seen at different angles. Subjects saw all of them simultaneously and were not forced to do the task

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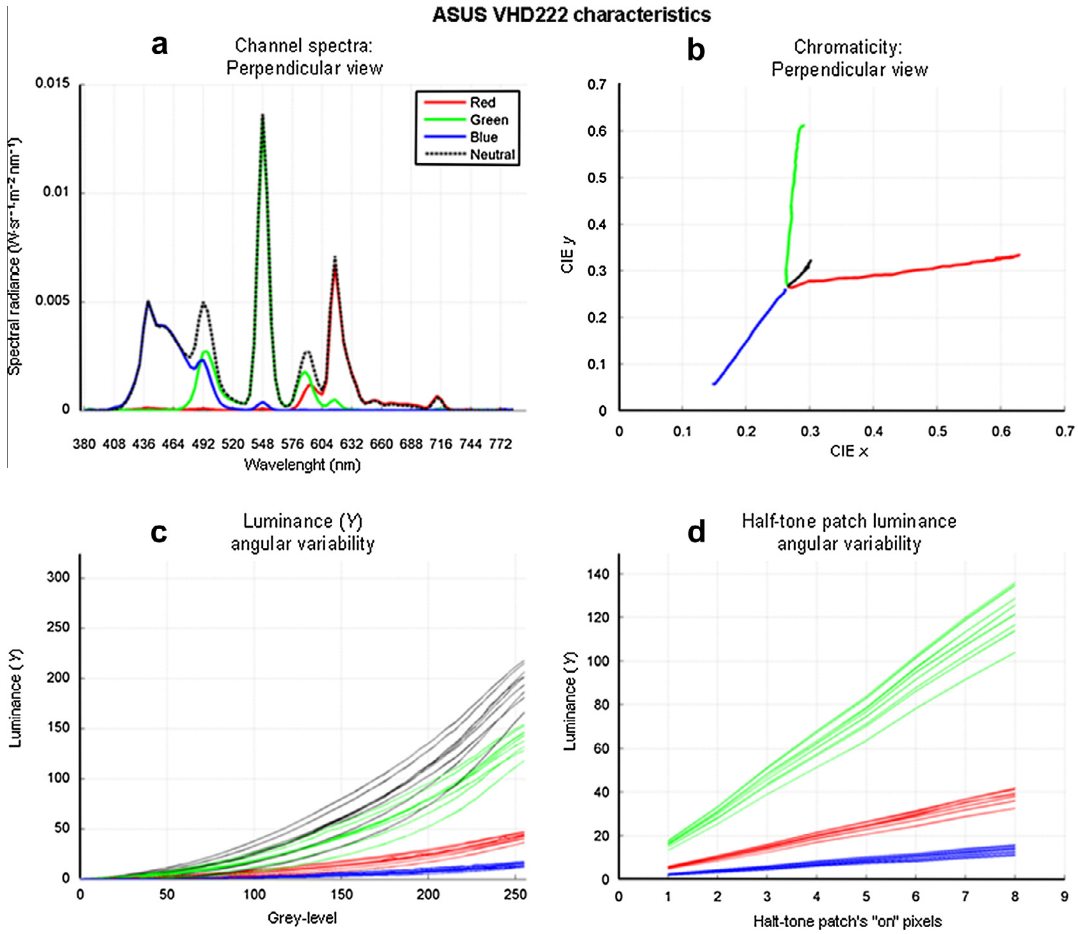

Fig. 4. Colorimetric measurements for the ASUS VHD222. Panel (a) shows the spectral radiance of the three chromatic channels (R, G, B) and their achromatic combination (W). Panel (b) shows the CIExy coordinates of the R, G, B, W patches for 256 different grey-levels. Panel (c) shows the variability of the gamma transfer functions measured for the R, G, B, W channels. Each curve corresponds to a different angular view. Panel (d) shows the luminance measured from each of the half-tone patches shown in Fig. 2. Each patch is represented in the x-axis by its number of "bright" pixels. Different curves represent different angular views. Data in panels (a) and (b) was obtained by pointing the measurement instrument perpendicularly to the monitor.

in any particular order. The angular separation between the centres of consecutive horizontal stimuli was 7° and between stimuli on the top row and bottom rows was 17.7°. Consequently, the left-most and rightmost square centres were located 10.5° off-axis. There were 3 experimental conditions corresponding the R, G, and B chromatic planes of the monitor: R-only patterns, G-only patterns and B-only patterns. Experiment 1 lasted no more than 15 min and subjects were allowed to rest between experiments.

2.2.2. Experiment 2 (serial matching)

All eight patterns were presented at each of 5 different viewing angles. Patterns were presented one at the time in 5 locations on the LCD screen: perpendicular, top, bottom, left and right. The centres of these locations subtended 5° (top and bottom patterns) and 8° (left and right patterns) from the line of the observer's gaze perpendicular to the screen. The angles were chosen as a conservative estimate of the angles subtended by the extreme stimuli in Xiao et al. plus an allowance for small head movements. Subjects did not manipulate sliding bars but instead pressed buttons on a keyboard to increase or decrease the luminance at the centre of each pattern. Patterns were not circular but square, to avoid aliasing problems and there was a Gaussian roll-off to smooth the interface between the half-tone patch and the uniform central patch. The eight stimuli were presented in a randomised manner (subjects did not know which half-tone patch or colour was to be presented next nor in which position) and were not repeated. The starting luminance of the central patch was estimated from previous results with up to 20% random luminance added. The experimental sequence started with a uniform grey screen adaptation that lasted 5 s followed the trials sequence. Between sequential presentations (trials) there was a mask made of random colour patches (the same size as the original patches) that lasted 7 s. Each of the nine subjects did 120 trials (8 intensities, 3 chromatic conditions and 5 screen locations). The experiment lasted between 1 and 1.5 h, including a 10-min training session before at the beginning. The hardware and the task was similar to that of Experiment 1.

2.3. Free viewing conditions experiments on multiple LCD displays

2.3.1. Experiment 3 (serial, free viewing)

A third experiment was performed in a large environment under artificial fluorescent lighting and plain white walls. The objective of this experiment was to simulate a common "office" environment, which includes coloured objects and multiple inter-reflexions. In Experiment 3 the stimuli were presented sequentially at the centre of the screen and head stability was also enforced by means of a chin rest. Nine subjects performed the same matching task as in the previous experiments, except that only a single stimulus was presented at the centre of the screen at a time. Experiment 3 was performed on the same LCD screens detailed in Table 1 plus an extra laptop (Toshiba Tecra M9 – Twisted Nematic technology – 1440 × 900 resolution). The resolution of the extra

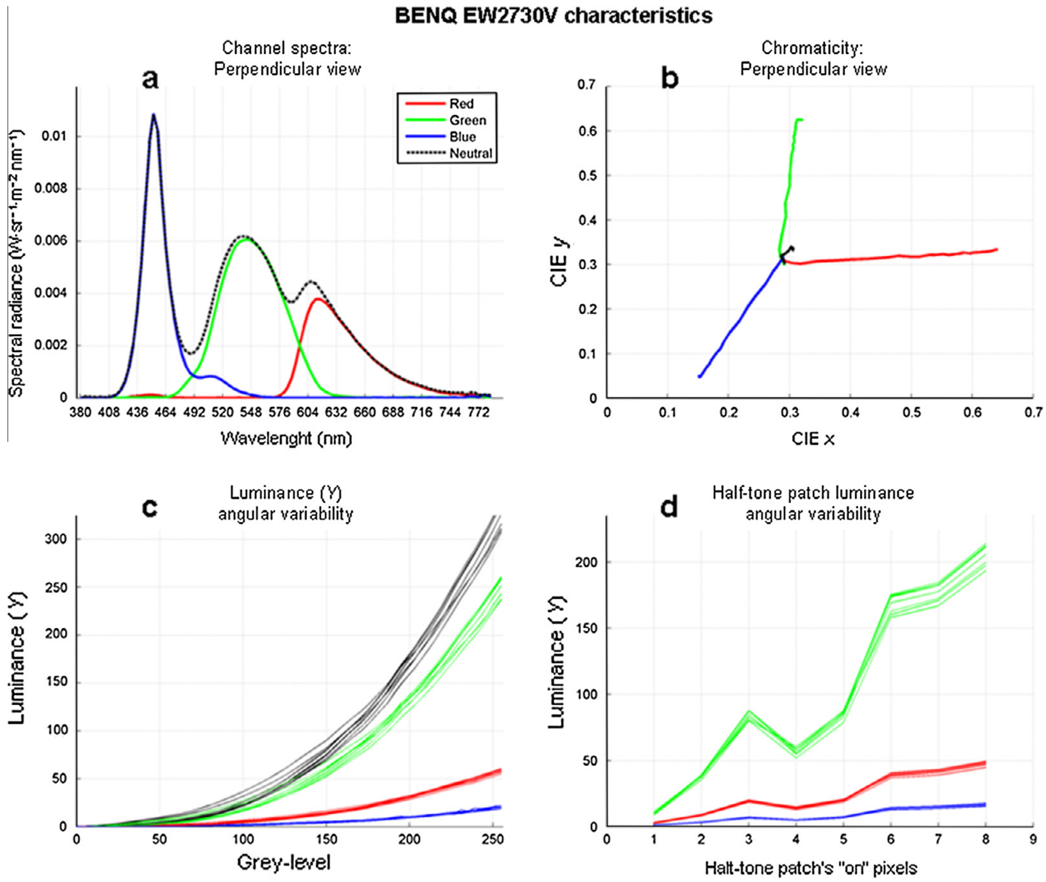

Fig. 5. Colorimetric measurements for the BENQ EW2730V. Panel (a) shows the spectral radiance of the three chromatic channels (R, G, B) and their achromatic combination (W). Panel (b) shows the CIExy coordinates of the R, G, B, W patches for 256 different grey-levels. Panel (c) shows the variability of the gamma transfer functions measured for the R, G, B, W channels. Each curve corresponds to a different angular view. Panel (d) shows the luminance measured from each of the half-tone patches shown in Fig. 2. Each patch is represented in the *x*-axis by its number of "bright" pixels. Different curves represent different angular views. Data in panels (a) and (b) was obtained by pointing the measurement instrument perpendicularly to the monitor.

screen was 1440 × 900 pixels. To be able to avoid delays in unplugging the LCD screens and perform the experiments faster, monitors were run simultaneously from different computers (details in Table 1). Observer's distance to the screen (i.e. angular viewing conditions) was 90 cm and stimuli was presented centrally (perpendicular viewing).

3. Results

3.1. Colorimetric measures

The LCD screens in Table 1 were measured to investigate their output dependence on grey-level input. The first measurement, patches of R, G and B-only pixels and their achromatic combination (W) were displayed at the centre of the screen and its full spectral radiance measured at 2 nm sampling resolution in the range 380–780 nm. These measurements were made inside a dark room and at a direction perpendicular to the plane of the screen ($\alpha = 0°$ in Fig. 2). The display background around the central patch was set to black to avoid interference from stray light. To obtain the chromatic dependency of the R, G, B and W channels on the grey-levels of the display, we created uniform patches using ramps of 255 values (grey-levels) which produced luminances ranging from 0 to the maximum luminance of each channel. From the full spectroradiometric measures, colorimetric measures (in the CIExy and CIELab spaces) were produced and plotted in terms of their dependence with the corresponding grey-level.

The measurements of the central patch were repeated from the nine angles and directions detailed in Table 2. The angles were chosen to cover the approximate angles of viewing commonly present when sitting at a distance of about 60 cm from a large (27 in.) LCD screen which also correspond to viewing the user interface shown in Fig. 2. The last measurement was repeated with the central patch replaced by a half-tone patch (see Fig. 2) of the same size and position.

Fig. 4 shows a summary of our colorimetric measures for the ASUS VHD222 screen. Since our aim is to highlight the variability of these measures with viewing angle and grey-level value, some details have been omitted from the plots (e.g. individual curves are not labelled in panels (c) and (d)).

The chromaticities of all the measured patches (for all grey-levels) are shown in panel (b). The small curvature near the end of the plots reveals that the R, G, B and W channels lose their linearity at high-luminance levels. In the same panel, the achromatic locus should be a single point and it turns out to be a line (see black line), revealing a chromatic shift for the W patches as luminance increases. The plots of panel (c) show how viewing angle clearly influences the measured value of luminance (Y) for all the channels considered. This is especially true for the neutral (W, shown in black lines) and green (G) channel. Plots in panel (d) show that the half-tone patches also present differences in luminance with respect to viewing angle, following similar patterns as the uniform patches in panel (c). Predictably, the HP LE1711 screen, which shares the same technology, shows nearly identical results to those of Fig. 4 (not included here).

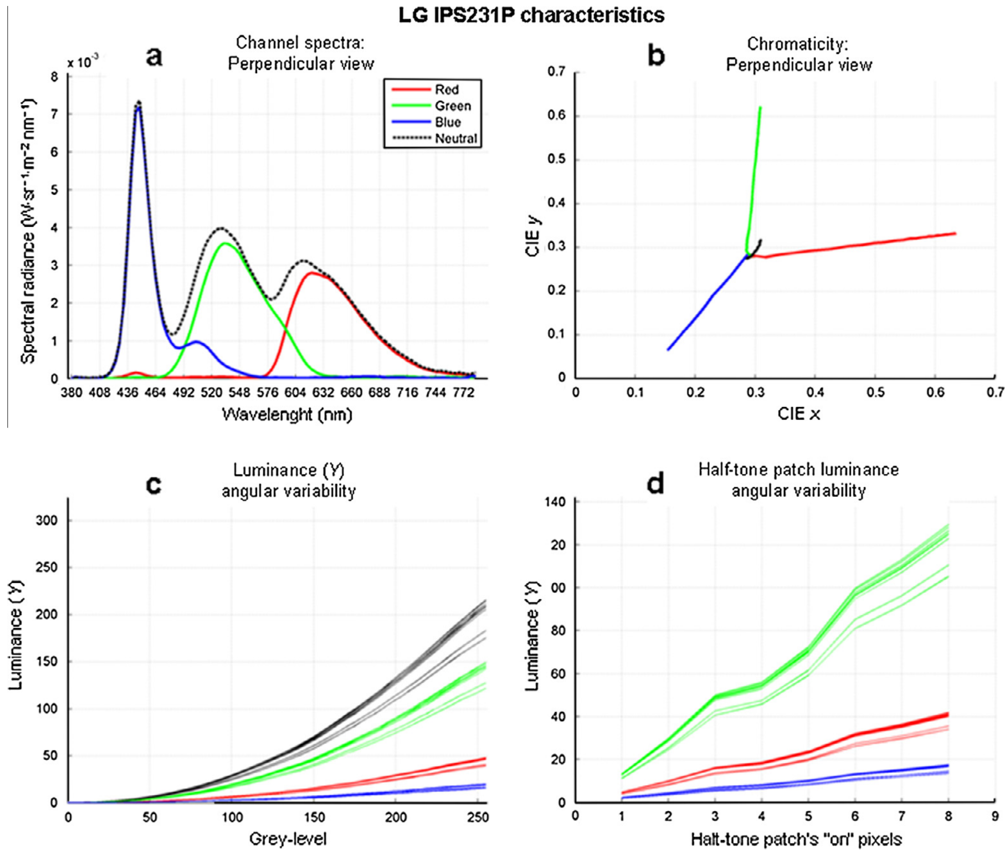

Fig. 6. Colorimetric measurements for the LG IPS231P. Panel (a) shows the spectral radiance of the three chromatic channels (R, G, B) and their achromatic combination (W). Panel (b) shows the CIExy coordinates of the R, G, B, W patches for 256 different grey-levels. Panel (c) shows the variability of the gamma transfer functions measured for the R, G, B, W channels. Each curve corresponds to a different angular view. Panel (d) shows the luminance measured from each of the half-tone patches shown in Fig. 2. Each patch is represented in the *x*-axis by its number of "bright" pixels. Different curves represent different angular views. Data in panels (a) and (b) was obtained by pointing the measurement instrument perpendicularly to the monitor.

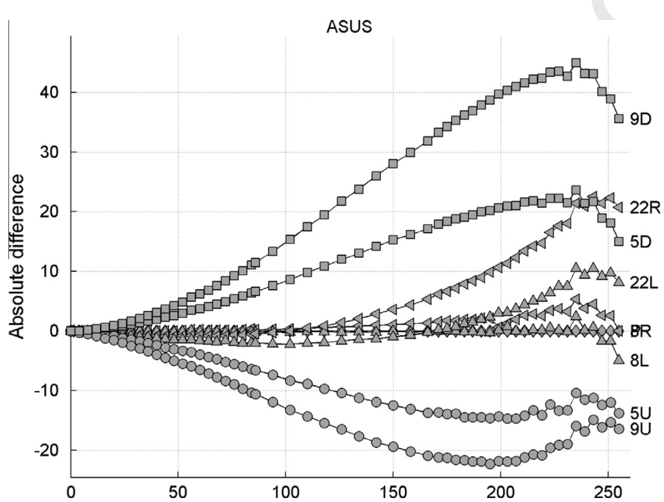

Fig. 7. Colorimetric measurements for the ASUS VH222D screen showing the luminance differences (in Cd/m^2) between the gamma transfer function measured perpendicularly (P) and those measured at different angles (for an explanation on the labels see Table 2).

Fig. 5 shows similar measurements for the BENQ EW2730V screen. The plots follow the same trends as in Fig. 4: lines in panel (b) are also curved at their saturated end and the black line (which should be a single point) is similar to the black line in the previous plot. Panel (c) shows a similar (although less marked) variability of the gamma curves with viewing angle. However, the main difference between both LCD screens can be seen in panel (d), corresponding to the OETF measured from half-tone patches. The plots of panel (d) are clearly non-linear and non-monotonic: the luminance averaged from half-tone patches with 4 and 5 bright pixels measurements is clearly lower than the luminance averaged from patches with 3 bright pixels. This might be an effect of the interaction between our measurement instrument and this particular screen. The same trend is followed by the three channels (although more strongly by the G channel).

Fig. 6 shows the results for the other monitor measured (the LG IPS231P) which arguably produced similar plots to those of the previous figure. The dip in the luminance dependency with number of bright pixels in the half-tone patch in panel (d) was less pronounced than for the BENQ EW2730V (Fig. 5), although still of concern for our experiment.

The relationship between the different curves in panels (c) is also non-linear. Fig. 7 shows the luminance difference (in Cd/m^2) between measures of solid patches taken perpendicularly and those taken for different viewing angles for the ASUS VH222D screen. The figure shows that the effects of viewing angle increase with the grey-level value (luminance) of the pixels except perhaps for the highest luminance values, where they decrease. This difference is larger for the up (U) and down (D) viewing directions, as expected [9]. This behaviour is common to all the LCD screens we tested. For solid W channel patches, there is a deviation in the chromaticity of light emitted by the LCD cells towards yellow as the voltage increases. Also looking at panels (b) we can see that

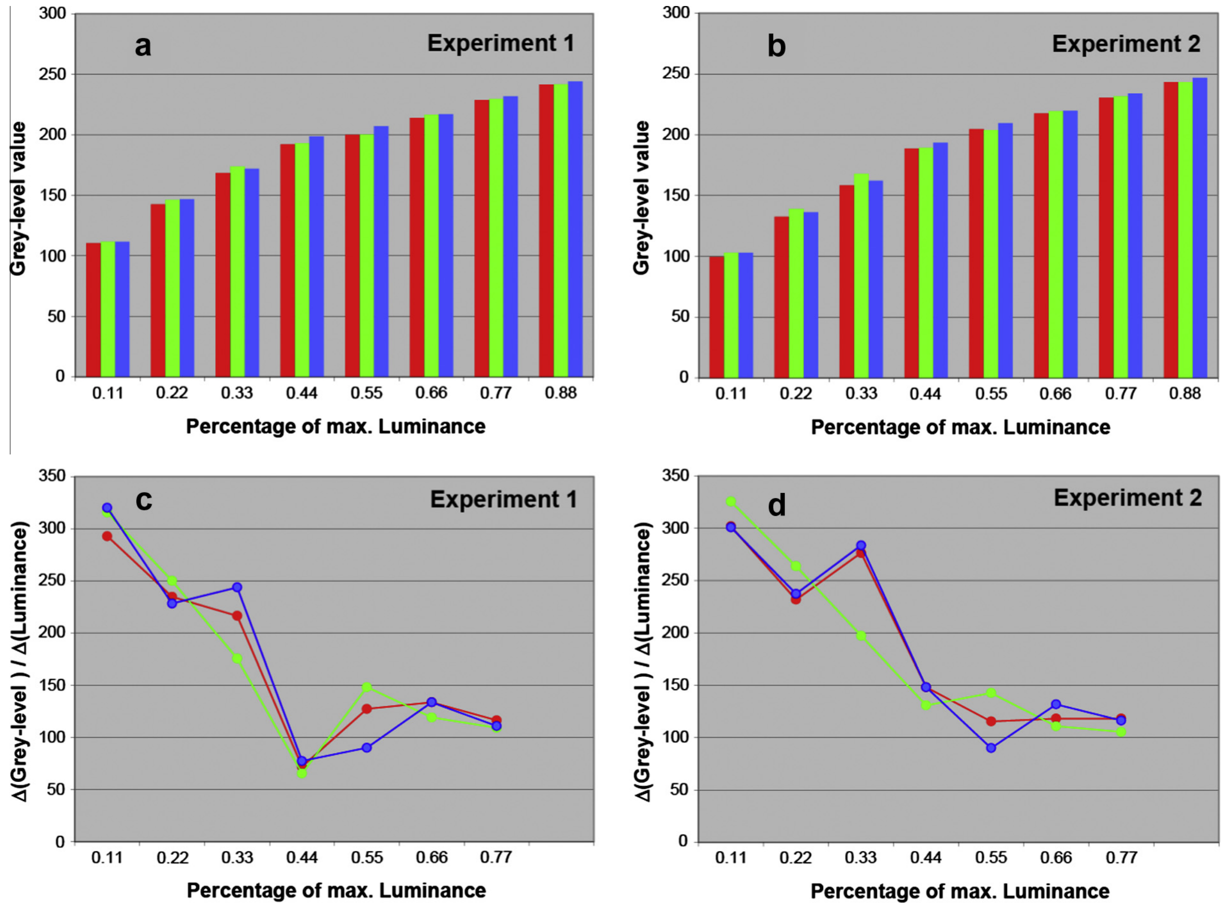

Fig. 8. Summary of results for *Experiments 1* and *2* (all subjects and chromatic conditions). Panels (a) and (b) at the top show the corresponding average adjustment (in grey-levels) for all subjects as a function of relative luminance for the two experiments. Panels (c) and (d) at the bottom show the approximate slope of the results of the corresponding experiment (top panels), for all chromatic conditions. Each level is represented in the *x*-axis as a % of the total luminance available.

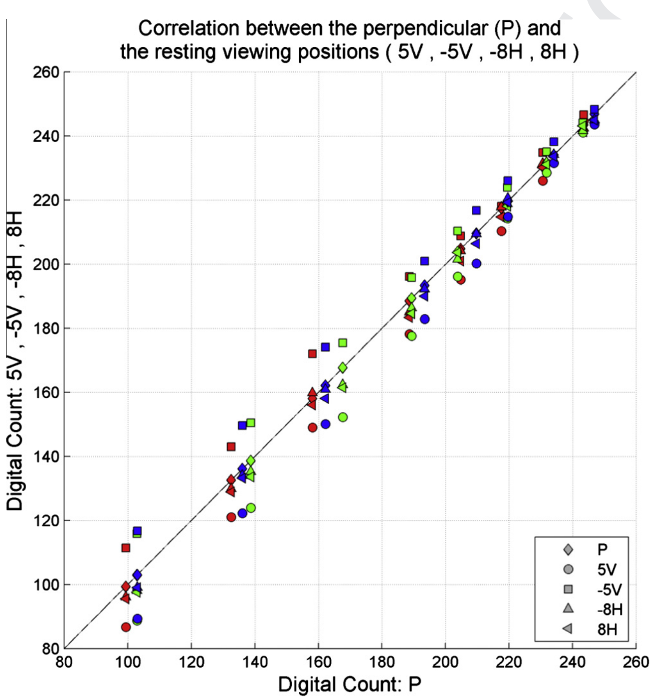

Fig. 9. Comparison of the grey-level values obtained for non-perpendicular viewing against perpendicular viewing.

different technologies perform differently. Take for instance the LG monitor, its CIE chromaticity lines are straighter than those of other monitors and the W line is shorter. Panels (a), which show spectral radiance curves, clearly identify the different technologies as well, being the IPS and VA curves smoother than the TN. In the case of dithering patterns analysed in panels (d) two of the monitors (the LG and the BENQ, corresponding to IPS and VA technologies) experience a noticeable dip in the middle part of its gamma transfer function, i.e. dithering textures with 44% and 55% of the maximum intensity level.

We have seen that the monitors we measured present differences both in terms of the light they emit and with respect of the viewing angle. In the next section we will test whether these differences are reflected in the psychophysical performance of human observers.

3.2. Psychophysical results

3.2.1. Experiment 1 (parallel matching)

Panel (a) in Fig. 8 summarizes the results for Experiment 1. The abscissa shows the percentage of the maximum luminance that each half-tone patch should emit (1 bright pixel = 11%, 2 bright pixels = 22%, etc.) The ordinate shows the average adjustment values (in grey-levels) that observers set to match the half-tone patches. Relatively high digital counts (>100) were needed to match low luminance levels. Despite having only 11% of the total

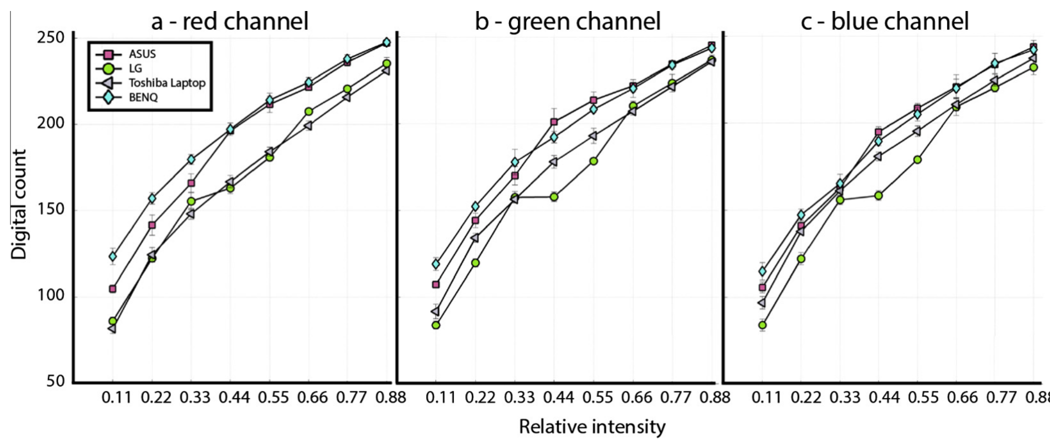

Fig. 10. Psychophysical results of *Experiment 3* to determine the gamma transfer function. Each point corresponds to a match between the central square and the surrounding dithering pattern. The *x*-axis represents the intensity of the dithering pattern as a fraction of maximum intensity. *Y* axis shows the grey level value of the central (uniform) patch necessary to match the surrounding. Different curves correspond to different monitors. Panels a, b and c correspond to the red, green and blue channels respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

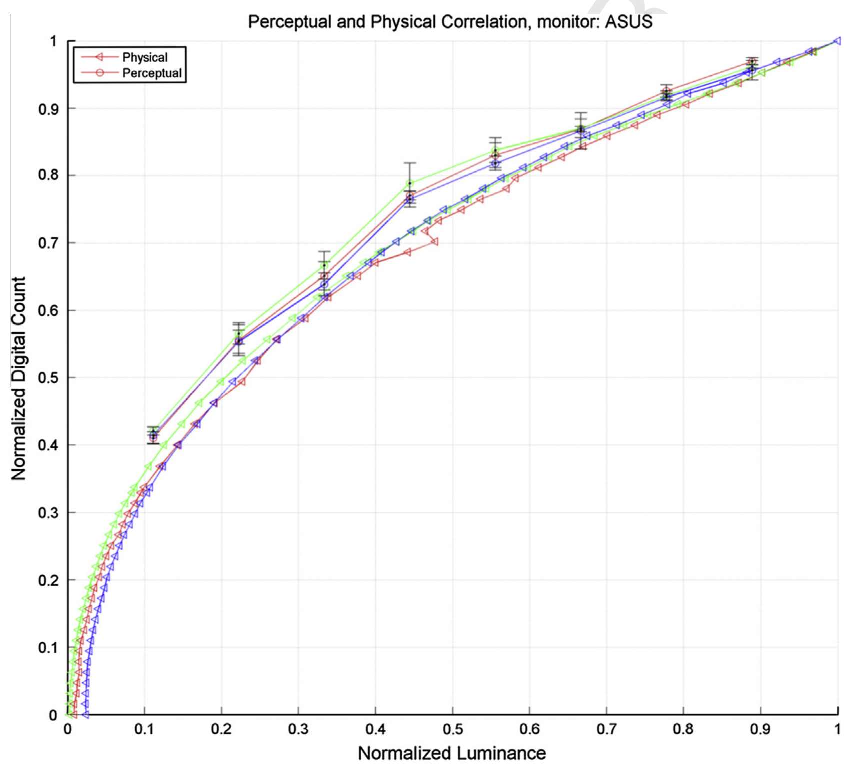

Fig. 11. Psychophysical and colorimetric results for the ASUS VH222D monitor. The *x* axis shows the luminance values (normalized to its maximum value) and the *y* axis shows the grey-level values necessary to produce (match) the corresponding luminance (circles). The triangles correspond to the colorimetric measures of the uniform screen patches. Colours represent the three monitor phosphors. Error bars show the standard deviations for nine human observers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

luminance of the monitor, the darkest half-tone patches were matched to nearly 100 grey-levels (which correspond to 39% of the total monitor luminance).

The local slopes of the data plotted in panel (a) (Fig. 8) are plotted in panel (c) of the same figure, where each circle shows the ratio Δgrey-level/Δluminance, discriminated for the R, G and B channels. The resulting plot indicates that the growth of the curve is non-linear, showing a pronounced dip for half-tone patches whose luminance is increased from 33% to 44% of the maximum luminance value.

3.2.2. *Experiment 2 (serial matching)*

For comparison with the previous results, we plotted the results for the central stimulus of Experiment 2 ($\alpha = 0$, perpendicular viewing) in panels (b) and (d) of Fig. 8. Panel (b) shows a summary of the results for all subjects considering only the central patch and panel (d) shows a plot of the local slope at each point of the curve in panel (b). The relationships are similar to the ones shown before, except that for the absence of the dip. The results for the G-channel are the most monotonic, consistent with the theoretical predictions. The other channels show some variations, in particular a

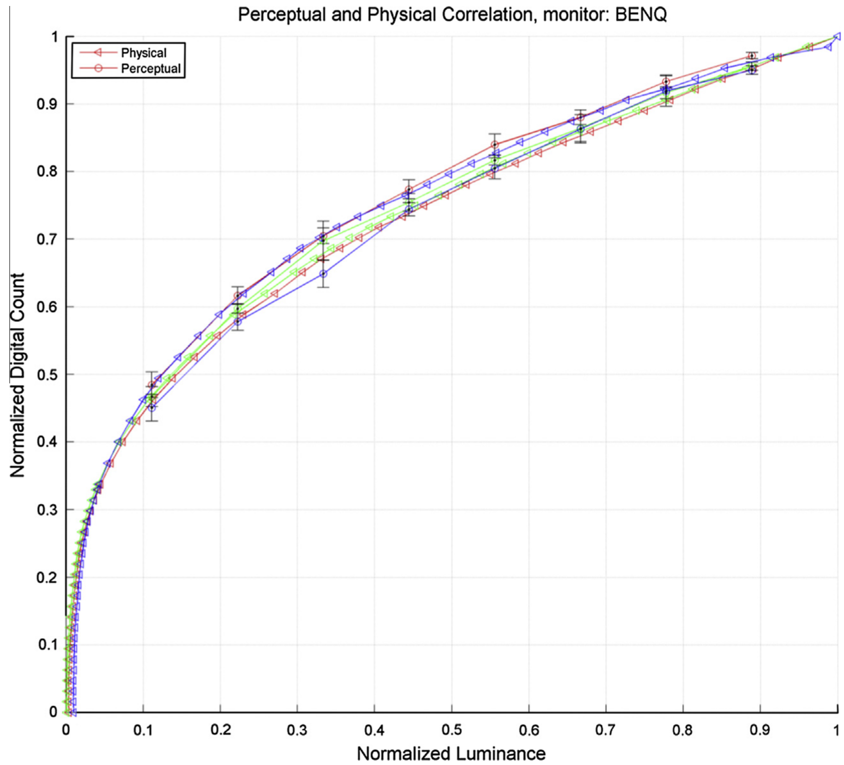

Fig. 12. Psychophysical and colorimetric results for the BENQ EW2730V monitor. The *x* axis shows the luminance values (normalized to its maximum value) and the *y* axis shows the grey-level values necessary to produce (match) the corresponding luminance (circles). The triangles correspond to the colorimetric measures of the uniform screen patches. Colours represent the three monitor phosphors. Error bars show the standard deviations for nine human observers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

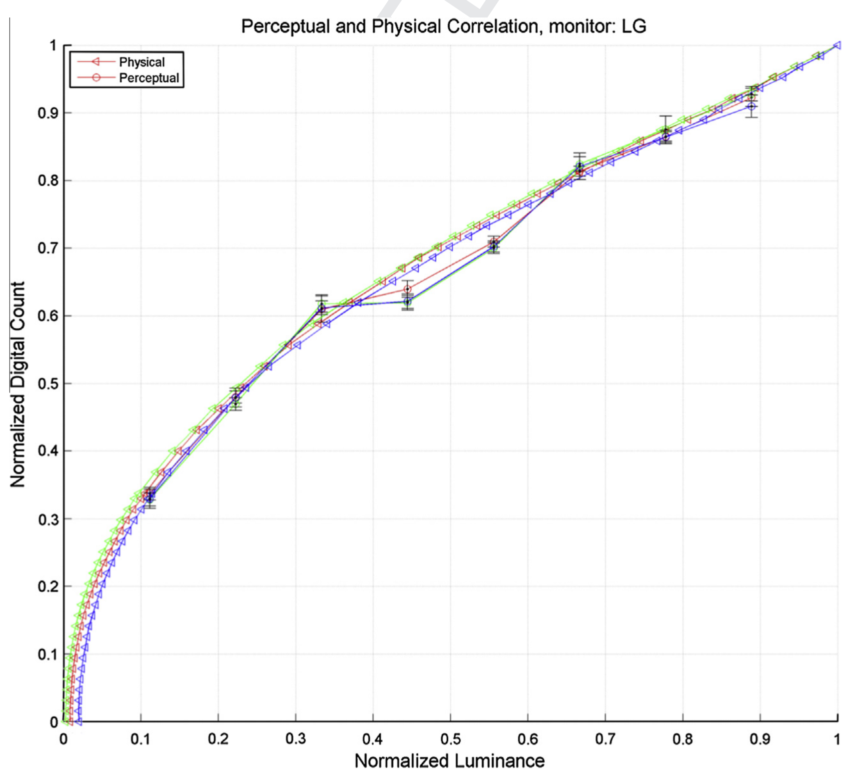

Fig. 13. Psychophysical and colorimetric results for the LG IPS231P monitor. The *x*-axis shows the luminance values (normalized to its maximum) and the *y*-axis shows the grey-level values necessary to match the corresponding luminance (circles). The triangles correspond to the colorimetric measures of the uniform screen patches. Colours represent the three monitor phosphors. Error bars show the standard deviations for nine human observers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

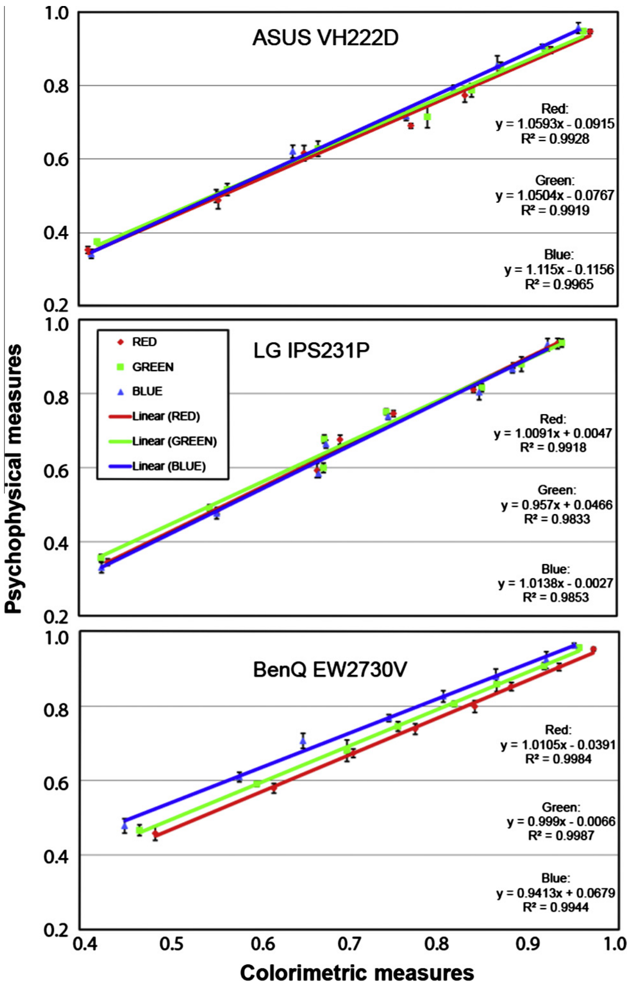

Fig. 14. Correlation between the colorimetric measures and psychophysical data for the ASUS VH222D, the LG IPS231P and the BENQ EW2730V monitors. All values were normalized to its maximum and error bars show the standard deviations for nine human observers.

sudden change in slope for the red and blue phosphorous when increasing the percentage of luminance from 33% to 44%.

Fig. 9 summarizes the variations in the results occurring for different viewing angles. In the figure, all results have been plotted against the results obtained for the perpendicular viewing condition in terms of grey-level value set by the subjects in the match (see Fig. 8). The figure contains the averaged results for all 9 subjects but discriminating for intensities, viewing angles and channels. As a result, the diagonal line contains the points corresponding to the perpendicular view (diamonds) while other symbols correspond to other viewing angles (see legend).

The plots of Fig. 9 show that despite the uniformity of the luminance steps (11%), subjects adjusted the digital count in a non uniform manner, as expected for a gamma function. For vertical angular shifts (square and round symbols), subject responses show the largest and most consistent differences. Moreover, the direction of the angular shift (up or down) correlates with similar subject results, thus when the shift is up the values decrease and when the shift is down the values increase with respect to the diagonal (no angular shift). This effect decays as the relative luminance increases (points tend to converge to the diagonal for higher luminance). There is also very little influence of the horizontal viewing shifts on our results (all triangles are near the diagonal line).

3.2.3. Experiment 3 (serial, free viewing)

Fig. 10 illustrates the results for the three chromatic channels (each line corresponds to a particular monitor, as detailed in the caption). Error bars correspond to the standard deviations of the measurements obtained for nine subjects. Notice that there is no difference among channels regarding the shape of the curves for the same monitors. The "dips" obtained for the 4th and 5th dithering patterns (44% and 55% of maximum luminance) using the spectroradiometer are not apparent in the psychophysical measures for the BENQ monitor. However, they persisted in the case of the LG monitor. A possible explanation is that they are caused by variations in the characteristics of the light (e.g. polarization, flickering, etc.) from both monitors which influence the instrument but observers only notice in the case of the LG monitor. Also the smoother curves correspond to the BENQ monitor and the Toshiba laptop, which are at opposite ends of the price range.

4. Discussion

4.1. Perceptual and colorimetric data

Figs. 11–13 show the superimposition of the perceptual and colorimetric data that was presented in the previous section for the monitors of Table 1.

The curves in Fig. 11 show a close agreement between the data (in grey-levels) obtained by colorimetric methods and that obtained by psychophysical methods. There is a systematic shift upwards of the psychophysical with respect to the colorimetric data, i.e. subjects assigned a slightly higher grey-level value than

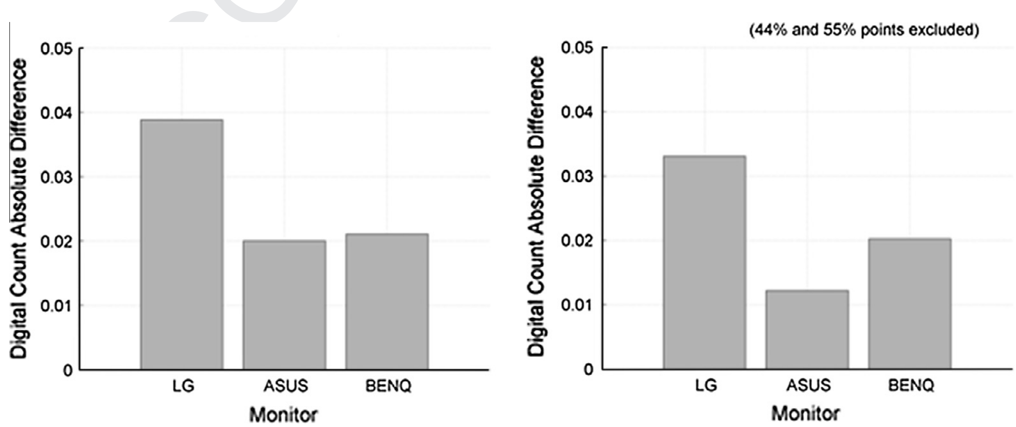

Fig. 15. Sum of the absolute differences between the psychophysical measures and the colorimetric measures for each of the monitors tested. The right plot shows how this changed when the two mid-luminance data points (44% and 55% of MAX luminance) are removed.

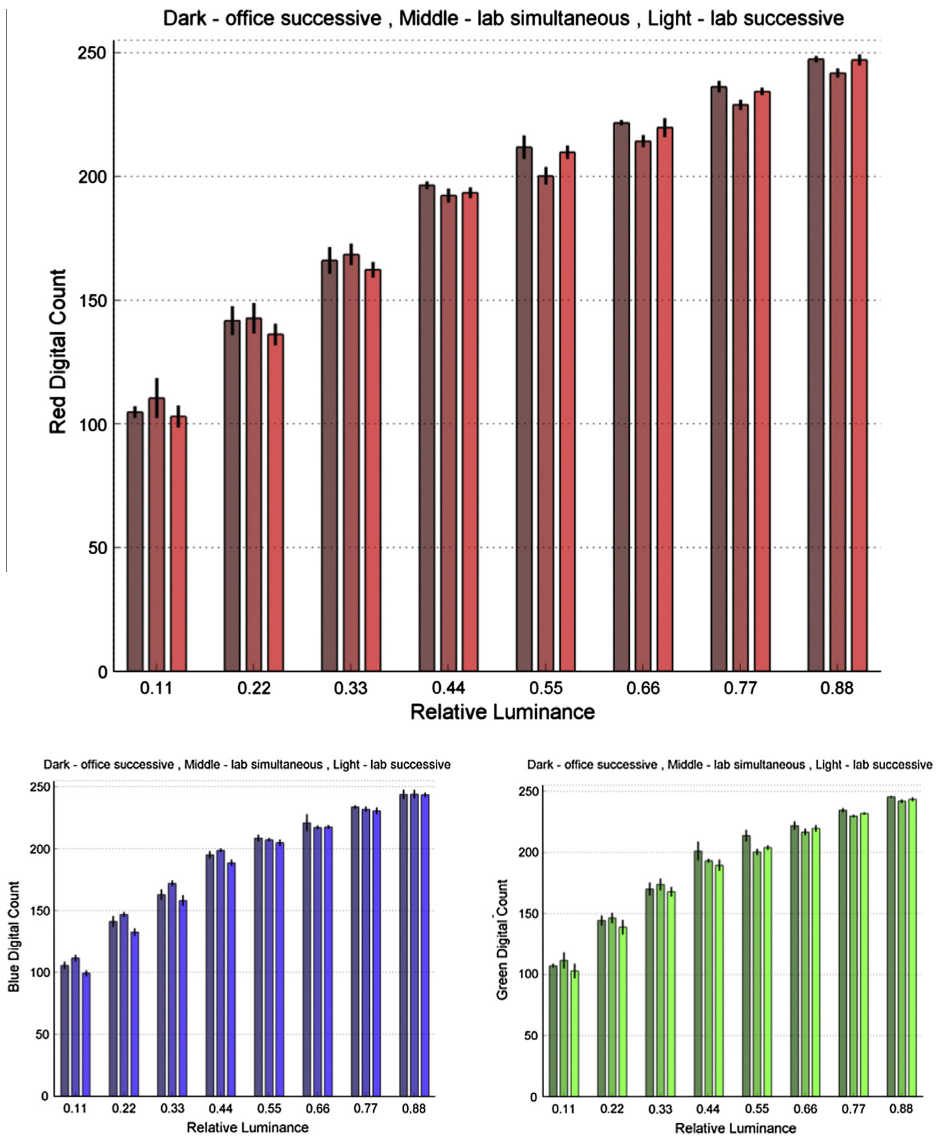

Fig. 16. Psychophysical data collected for the ASUS monitor in lab conditions and in an "office-like" environment and in parallel and sequential presentations (first and second experiments). Black crosses correspond to standard deviations.

that calculated by the instrument. There are many possible reasons for this, which include issues regarding light polarization and flickering and their interactions with the spectroradiometer. This shift is not apparent in other monitor's data (see below).

The BENQ monitor shows the highest agreement between colorimetric and psychophysical data (the curves in Fig. 12 are practically superimposed, well within the limits of the error bars). The consistency within subjects is also remarkably high for this particular monitor.

The LG monitor (see Fig. 13) is the only one where the colorimetrically-measured "dip" is also mirrored by the psychophysical results. The most likely cause of this dip is the rapid inversion of polarity in LCD cells, which is applied to prevent permanent damage in liquid crystal materials.[2] This inversion of voltage is applied on alternate video frames and in anti-phase regarding nearby pixels, thus approximately cancelling brightness artefacts (flicker). Voltage inversion can become apparent in some monitor/half-tone pattern configurations. We speculate here that these flickering patterns (visible only in the LG screen) are the best explanation for the dip in Fig. 13. A deeper study of this particular technology may reveal the exact causes of this phenomenon.

Fig. 14 shows the correlations between the psychophysically collected results and their corresponding colorimetric measurements (for each monitor and half-tone pattern). Error bars correspond to standard deviations in the case of the psychophysical measures. The best fitting lines and corresponding R^2 correlation coefficient are shown in the plots for the R, G and B phosphors. In all cases the data follows straight lines, with R^2 values close to 1, showing that the psychophysical experiments have a strong correspondence with the colorimetric data, indeed human observers can be used to determine the gamma transfer function of LCD monitors. For the ASUS monitor, the slope of the fit is the most different from one, reflecting the linear shift between both sets of data. The differences between the three (RGB) monitor channels are very small except in the case of the BENQ monitor.

Fig. 15 shows the absolute difference (the sum of the differences between the colorimetric and psychophysical measures) in terms

[2] See an explanation and screen test patterns online at http://www.techmind.org/lcd/.

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of percentage of the maximum value. The data shows that if we use this as a quality measure of the correspondence between what observers do and what a photometer does, the LG monitor does almost twice as bad as the BENQ and the ASUS. This is probably because of the presence of the two central patterns (44% and 55% of maximum luminance) which seem to be problematic in this particular LCD screen technology and model. The right panel in Fig. 15 shows the same results when the two "problematic" points are removed.

4.2. Effects of illumination environment

Finally, we tested how the psychophysical results differ when measured in office conditions (artificial illumination). Only the ASUS LCD screen was tested under both (lab and office) conditions and its results are shown in Fig. 16. A visual inspection of the figure suggests that all channels behaved in a similar way (see dark bars in all three panels). We expanded the plot of the red channel to show these particular results. For comparison, we also included the results obtained for the Experiment 1 "parallel" (light bars) and Experiment 2 "simultaneous" (middle bars), where the difference is noticeable.

5. Conclusions

We tested the effects of viewing angle on three of the most common LCD monitor technologies in the market using half-tone patterns. Our results show that observing the screen from a vertically slanted viewpoint incorporates a noticeable bias in the outcome of perceptual matching experiments using half-tone patterns, similar to those of Xiao et al. [1]. Our results were also confirmed by colorimetric measures. Considering this, we implemented a sequential version of the same experiments and, as expected, the new paradigm removed all angular dependency from the results. A third batch of experiments was conducted to reproduce more "office-like" conditions and to test the performance of observers with other LCD technologies which claim to be an improvement from Twisted Nematic, the most popular one. To this end, five different types of LCD monitors were tested. We concentrated our study on the ones most likely to take over the market (IPS, VA) and the most common one at the moment (TN). Given that we only tested one LCD unit per technology type, our results cannot be said to be representative of the whole spectrum, however, they hint of how reliable these types of measurements are likely to be if extended. For this reason, results regarding any particular type of technology have to be considered in this context, since the problems identified here could be dependent on the particular characteristics of the LCD monitor tested or even be caused by an exceptional unit.

The third experiment identified a type of brand/technology (LG/IPS) under which observers do not perform as expected when exposed to dithering patterns in the mid-luminance range. We recommend that these LCD monitors are either identified before conducting the test or that the mid-luminance dithering patterns are removed from the experimental set-up and the corresponding points interpolated from the rest of the curve. In the future it might be desirable to expand this kind of test to other technologies including more portable devices, such as iPods, tablets and PDAs, whose gamma transfer function could also be estimated in this manner.

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