Displays 33 (2012) 46–53

Contents lists available at SciVerse ScienceDirect

Displays

journal homepage: www.elsevier.com/locate/displa

How human perceptions of Mura affect LCD market values

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ARTICLE INFO

Article history:
Received 12 January 2011
Received in revised form 21 August 2011
Accepted 13 December 2011
Available online 29 December 2011

Keywords:
LCD Mura
Markdown Price
Response Time
Decision Time

ABSTRACT

Liquid crystal displays (LCDs) hold a large share of the flat-panel display market because LCDs offer advantages such as low power consumption, low radiation, and good image quality. However, image defects, such as spotlight, uniformity, and Mura defects, can impair the quality of an LCD. This research examined human perceptions of region-Mura and used Response Time and subjective markdown price to indicate the various severity levels of region-Mura that appeared at different display locations.

The results indicate that, within a specific Mura Level range, the Mura's location has a considerable impact on perceived quality ($p < 0.001$). Mura on the centers of LCDs have more impact than Mura on the corners of LCDs. Not all peripheral Mura were considered to be equal; participants chose different price markdown prices for LCDs with Mura in lower corners than they chose for LCDs with Mura in upper corners. These findings suggest that a manufacturer should establish a scraping threshold for LCDs based on information regarding Mura location to avoid the production waste from scrapping those LCDs, and should rotate the panel to position the most severe Mura in the lower part of the display to obtain a better perceived quality.

1. Introduction

Thin-film transistor liquid crystal displays (TFT-LCDs) have the largest share in the flat-panel display (FPD) market [10]. LCDs deliver full-color display capabilities, low power consumption, low radiation, and low weight, but some LCDs have noticeably non-uniform brightness problems, called Mura. Mura are imperfections of a pixel matrix surface that are typically larger than a single pixel, and that are visible when the display screen is driven to a constant gray level [21,23]. Various physical factors, such as non-uniformly distributed liquid crystal material and foreign particles within the liquid crystal, produce Mura in LCDs. Depending on their shapes and sizes, Mura defects may be classified as spot-Mura, line-Mura, and region-Mura defects [8], as shown in Fig. 1.

1.1. Mura detection

Quality issues related to Mura affect not only display price, but also overall end-user satisfaction. Both the issue of whether a given Mura is acceptable and the issue of how much that Mura degrades the quality of the device depend on human perceptions [13].

The LCD manufacturing process stipulates that each finished panel must pass defect inspections, lighting tests, and other quality tests. Mura defect inspection is the most difficult of all these tests. End users often complain and refuse to accept LCDs that passed inspection but had Mura defects unrecognized by the inspectors. For many manufacturers, Mura inspection is an important milestone before an LCD can be released to the market.

Most LCD manufacturers are still using unassisted human eyesight to inspect Mura Levels [1,8,22]. However, different human inspectors return inconsistent findings [24]. Even the best human inspector tends to make inconsistent judgments at different times. In addition, human inspection may result in higher costs.

Machine vision has been advanced as a potential replacement for human inspection. In recent years, many studies have followed the framework proposed by VESA FPDM [21], which provides a flow chart for processing real images from LCD panels. For different types of Mura (line-, spot-, or region-), algorithms have been developed to distinguish screen locations with uneven uniformity [1–3,5–7,9,11,12,14,15,19,21,23,26,27] and to combine techniques such as thresholding and quality control to identify Mura candidates [8].

Region-Mura are particularly difficult to classify at some specific Mura Level because each region-Mura has an indistinct boundary with the monitor background [28]. In addition, machine inspection sometimes detects Mura that are not visible to humans due to the limited contrast sensitivity of human eyes.

1.2. Mura Level and human perception based inspection

Most Mura research approaches focus on the detection method. Algorithms are developed by which manufacturers can improve the Mura detection. However, end users' perceptions of Mura merit

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doi:10.1016/j.displa.2011.12.003

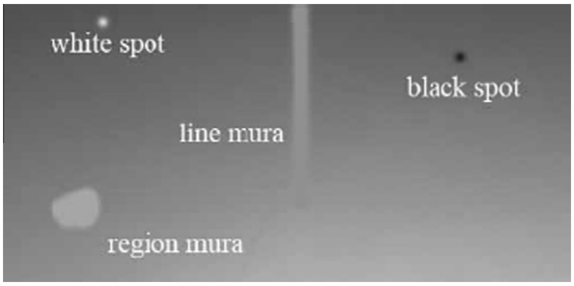

Fig. 1. Various types of Mura [26].

consideration. According to the SEMU standard, Mura Level (Q_I), which is used to measure the severity level of a region-Mura, can be expressed as $Q_I = |I_0 - I_b|/(1.97/A^{0.33} + 0.72)$, where A represents the area of a candidate region-Mura, and I_0 and I_b represent the luminance levels of the region-Mura and LCD background, respectively [8]. The JND (just-noticeable difference) concept is used to describe the relationship between Mura area and human perception ($\text{JND} = 1.97/A^{0.33} + 0.72$) [4], and $|I_0 - I_b|$ is the absolute average difference between a region-Mura and LCD background in the unit of luminance representing the local contrast of a candidate region-Mura. This formula indicates that a Mura with a large local contrast or a large area must have a high severity level.

1.3. Mura location

Although the SEMI Standard provides a guideline for Mura inspection [4], and the SEMU Standard provides a quantitative measurement of the severity of a region-Mura, both of them consider factors of Mura area and contrast. An end user performing actual tasks in practical computing environments might be more concerned with Mura location.

Tang et al. [11] investigated the effects of Mura location and Mura Level (Q_I) on human perception. Participants used markdown price as a dependent variable to express perceptions of the severity of a Mura. Mura location was defined as the distance between the center of a region-Mura and the center of a display. The result showed that when Q_I was between 2.6 and 4.7, a Mura close to the center of the display displeased end users more than an equivalent Mura far from the center. When Q_I was larger than 4.7 or smaller than 2.6, Mura location had little correlation with user satisfaction.

Tang's research [11] did not discuss how the Mura evaluation process affects the perceived quality of the display. In addition, questions such as: "Does the quadrant in which the Mura is located affect the perceived quality?" and "How does Mura detection time affect the perceived quality?" need to be further investigated. The present research answers these questions and makes inferences for LCD out-going quality control and pricing strategies.

2. Method

2.1. Subject

Twenty-four paid subjects participated in this study; ten subjects were female and fourteen were male. All of them had used computers for at least four years. The average age of the subjects was 21 years, with a standard deviation of 1.1 years. All subjects had normal or corrected-to-normal eyesight. Every participant had purchased computer displays in the past. Participants were paid NTD$100 per hour.

2.2. Experimental design

There were four independent variables in this experiment: Gender, Mura Level, Quadrant, and Distance. Mura Level ranged from 1.76 to 4.72, with 6 levels. The calculation of Mura Level was based on previous literature [8]. The Mura samples used in this study were modified from real Mura using Adobe Photoshop software to further control the Mura Levels. Fig. 2 shows some of the 95 Mura images used in the experiment. During the experiment, a set of such Mura images appeared randomly on the test LCD. Among the 95 Mura images, thirteen Mura images were blind tests; ten Mura images had randomly select Mura Levels and were randomly positioned. These 23 images were included to avoid learning effects. Seventy-two other Mura images were meaningfully positioned. Each meaningfully positioned Mura image was within 100 pixels of one of the diagonals of the LCD. Thus, there were four levels for the factor Quadrant: upper-left, lower-left, upper-right, and lower-right. The last factor was Distance, which was defined as the distance from the center of the display to the center of the Mura. There were three levels for Distance: Near, Medium, and Far. Any Distance of less than 360 pixels was defined as Near. Any Distance between 361 and 600 pixels was defined as Medium; any Distance farther than 600 pixels was defined as Far. There were 95 (6 Mura Levels $*$ 4 Quadrants $*$ 3 Distances + 13 blind tests + 10 randomly positioned) trials in each experimental block and each participant had to complete two blocks.

2.3. Experiment task

The examiners familiarized each participant with the experimental process and related information before the experiment began. In particular, participants were instructed to discount prices of defective LCDs based on their subjective preferences. Then, the participant began a training session which exactly resembled the formal experiment; this served to familiarize the participant with the experimental interface and procedure without time and performance pressures. The formal experiment started when the participant was ready.

Fig. 3 shows an example screen of the formal experiment. Note that the circle around the Mura did not show during the experiment before it was being identified by a participant. There are 95 screens, of which 72 present Mura along the diagonals of the LCD. Every time a Mura appears on the screen, the participant must find the Mura, move the mouse, and click on the Mura as soon as possible. Response Time is defined as the interval of time between the appearance of the Mura and the mouse-click. If the participant cannot identify any Mura on the screen, the "unrecognizable" button must be clicked. This button may be clicked if the Mura is too small, if the contrast between the Mura and the LCD background is too low, or if a blind test has been given.

When the participant has correctly detected and clicked on a Mura, the circle appears to indicate a correct answer, and the participant is asked: "Given that this LCD would normally be sold for NTD 10,000 (about USD 312.5), how much should it be marked down to make a customer willing to buy it?" The participant fills in this Markdown value in a text box through the experiment interface and presses the "Enter" key to end this trial. The time between the click on the Mura and the "Enter" keystroke is defined as Decision Time. The interface records the Response Time, Decision Time, and Markdown as dependent variables. Choosing markdown value as an index of evaluating market potential has been a common practice in production systems [16]. Particularly, price markdown is a mechanism to both match the market and customer expectation, when the product is or with defect [17].