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A consumer-grade LCD monitor for precise visual stimulation

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Abstract
Because they were used for decades to present visual stimuli in psychophysical and psychophysiological studies, cathode ray tubes (CRTs) used to be the gold standard for stimulus presentation in vision research. Recently, as CRTs have become increasingly rare in the market, researchers have started using various types of liquid-crystal display (LCD) monitors as a replacement for CRTs. However, LCDs are typically not cost-effective when used in vision research and often cannot reach the full capacity of a high refresh rate. In this study we measured the temporal and spatial characteristics of a consumer-grade LCD, and the results suggested that a consumer-grade LCD can successfully meet all the technical demands in vision research. The tested LCD, working in a flash style like that of CRTs, demonstrated perfect consistency for initial latencies across locations, yet showed poor spatial uniformity and sluggishness in reaching the requested luminance within the first frame. After these drawbacks were addressed through software corrections, the candidate monitor showed performance comparable or superior to that of CRTs in terms of both spatial and temporal homogeneity. The proposed solution can be used as a replacement for CRTs in vision research.

Keywords Vision research · Display · CRT · LCD · Consumer-grade

Cathode ray tube (CRT) monitors have long been the standard equipment for visual stimulus presentation in vision research. However, as it is increasingly difficult to acquire CRTs in working condition due to dwindling market demand, it is hard to find CRTs in vision labs nowadays. In contrast, the consumer market is dominated today by flat-panel displays, mainly liquid-crystal displays (LCDs). LCDs have many advantages over CRTs. For example, in comparison to CRTs, LCDs are more energy-efficient and compact, and they have the ability to show little or no visual flicker. On the other hand, LCDs also have some disadvantages. They are slow to respond and may produce motion blur as a result, and are also unable to reach certain black levels due to backlight leaking. However, LCD technology has developed rapidly in recent years, and LCDs have proven to be comparable or even superior to CRTs in displaying visual stimuli. For example, Wang and Nikolic (2011) extensively measured and analyzed the temporal properties of an LCD monitor, and showed that the monitor is suitable for vision research applications. However, they added a black frame after each stimulus frame (i.e., the refresh rates were reduced by half) to make the refresh rate comparable with that of the CRT monitors. Organic light-emitting diode (OLED) is another new type of display. Being thinner and lighter than an LCD, an OLED is capable of displaying deep black levels and achieving a higher contrast ratio than an LCD. Ito, Ogawa, and Sunaga (2013) provided extensive measurements of an OLED display (Sony PVM-2541, Sony Corp., Tokyo, Japan), and found it a high-quality replacement for CRT monitors. Unfortunately, OLED monitors are costly and rare, only available from Sony (Sony PVM and BVM series) at present.

Because CRT monitors have dominated the vision research field for a long time, much literature has been devoted to the temporal properties of CRTs (Bach, Meigen, & Strasburger, 1997; Brainard, Pelli, & Robson, 2002; Cowan, 1995; Sperling, 1971). In contrast, the temporal properties of LCDs have not been reported until recently. According to the literature, one of the most important differences between LCDs and CRTs is that LCD monitors present images continuously (hold type), whereas CRTs present images in a flash style (impulse type). Flash-display monitors (i.e., CRTs) have

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the disadvantage that the onset of the flash display might affect electrophysiological recordings (Krolak-Salmon et al., 2003; Williams, Mechler, Gordon, Shapley, & Hawken, 2004; Wollman & Palmer, 1995). However, there are also desirable advantages of flash-display over continuous-display monitors. For instance, the luminance of a stimulus remains relatively constant across display frames on flash-display monitors, whereas on continuous-display monitors the luminance gradually changes across the initial frames. Given that CRT monitors had maintained popularity among vision researchers until recent years, simulating flash-display monitors with LCDs could be a promising and potentially popular solution for precise visual presentation. One way to simulate flash display is to add a blank frame after each frame, to force the display to return to black, a method named "mimicked CRT" by Wang and Nikolic (2011). However, this approach has a significant weakness: Only half of the refresh rate capacity can be reached. For instance, if an LCD monitor has a maximal refresh rate of 120 Hz, it can only display stimuli at 60 Hz in the "mimicked CRT" mode.

In this article, we tested a consumer-grade LCD (ASUS PG278Q, Asus Global Pte., Ltd., Taipei, Taiwan) equipped with the Ultra Low Motion Blur technology (ULMB; NVIDIA, Santa Clara, USA) and found it comparable or even superior to CRTs in its performance. More importantly, it can reach a refresh rate as high as 144 Hz at a much lower cost than that of the Sony PVM and BVM series.

Method

Apparatus and measurement

The temporal and spatial luminance characteristics of a CRT monitor and two LCD monitors were tested. The CRT monitor (P1230, Dell Inc. TX, USA, referred to as "CRT") had maintained an excellent working condition after 10 years of use. The first LCD monitor (ASUS PG278Q) was tested in two different modes: once in the ULMB mode, which was our candidate and is referred to here as "LCD1-ULMB," and once in Overdrive (OD) mode, which we refer to as "LCD1-OD." The second monitor was an ASUS VG278 tested in the standard mode (LCD2). All the tested monitors were driven by an NVIDIA GeForce GTX 960 graphics card.

The monitors' configurations and basic luminance characteristics are shown in Table 1. The contrast was set to 50%, 80%, and 100% for LCD1, LCD2, and CRT, respectively. The luminance was set to 90% for LCD1 and CRT, and to 100% for LCD2. The resolution of the CRT was set to 1,024 × 768 pixels, and the LCDs were set to their native resolutions, which were 2,560 × 1,440 for LCD1 and 1,920 × 1,080 for LCD2. A refresh rate of 120 Hz was used for all monitors. The user-mode and the default-mode color temperatures were used for the LCDs and CRT, respectively. These settings were kept constant throughout the test.

Luminance was measured in two ways. First, a photodiode (BPW21R, Vishay Intertechnology, Inc. ShangHai, China) with a switch time below 1 μs was placed in the centers of different areas of the monitor to measure their temporal and spatial characteristics. Voltages, proportional to luminance changes, were amplified and recorded by an electrophysiology (EEG) recording system (Synamps II, Compumedics NeuroScan, Charlotte, USA) at a sampling rate of 10 kHz and were used to characterize the luminance properties of each monitor. The second method was to use a ColorCal MKII photometer (Cambridge Research Systems Ltd., Cambridge, UK) to measure the dependence of luminance on pixel location and viewing angle.

All measurements were taken in a dark room after the monitors had been turned on for at least 60 min, to minimize variation due to warming up (Klein, Zlatkova, Lauritzen, & Pierscionek, 2013). The study was approved by the Academic Committee of the College of Education, Soochow University. All of the Matlab code to analyze the data is available at ~~http://web.suda.edu.cn/yzhangpsy/projects.html~~.

Stimuli and procedure

To measure the spatial homogeneity of luminance, the whole display of each monitor was divided evenly into nine rectangular areas (appearing as a 3 × 3 grid). The centers of the nine areas were measured one by one in a random order. Test images were generated and displayed over these nine areas using Matlab (2011b; MathWorks Inc., Natick, USA) with Psychtoolbox (3.0.14; Pelli, 1997b).

Three series of tests were carried out using two different types of images. The first series tested the luminance dependence on pixel location and time (Pelli, 1997a). The test was based on presentation of a solid white ellipse fitting the inside of each rectangular area of the display, and measurements were made using the photodiode placed in the center of the ellipse over each area. Each location was tested for 50 trials, each of which consisted of a black display (100 ms) and an image (33.3 ms). A trigger was sent to the EEG amplifiers by the photodiode via a parallel port when the image appeared on the screen.

In addition to location dependence, the second test series also addressed the luminance's dependence on orientation. A full-contrast grating filling the whole display with a spatial frequency of two pixels per cycle was used. The stripes of the grating were oriented vertically, horizontally, or at an angle of 45° to the right. The luminance of the grating in each orientation at each of the nine locations was measured ten times with the photometer. The grating remained on the monitor for each measurement until the luminance readout became stable.

t1.1 **Table 1** Monitor configurations and basic luminance characteristics

Monitor	Refresh Rate (Hz)	Resolution (pixels)	Contrast (%)	Luminance (%)	Max. Luminance (cd/m^2)*	Min. Luminance (cd/m^2)*
LCD1-ULMB	120	2,560 × 1,440	50	90	136.166 ± 0.058	0.163 ± 0.004
LCD1-OD	120	2,560 × 1,440	50	90	364.375 ± 0.381	0.429 ± 0.013
LCD2	120	1,920 × 1,080	80	100	340.551 ± 0.074	5.125 ± 0.010
CRT	120	1,024 × 768	100	90	82.932 ± 0.427	0.032 ± 0.005

* Luminance is reported as the mean value ± standard deviation of the ten measurements.

The luminance dependence on viewing angle was measured in the third test series for the CRT and LCD1-ULMB (the candidate monitor). The luminance at the center of the screen was measured with the photometer 28.5 cm away from the screen center at seven viewing angles (– 45°, – 30°, – 15°, 0°, 15°, 30°, and 45°) along the horizontal meridian. The luminance at each viewing angle was measured five times and then normalized to the maximum luminance of each monitor measured at 0°.

Data analysis

To understand the spatial and temporal characteristics of the monitors, two parameters—initial latency and relative maximum luminance of the first frame (RML1st)—were calculated from luminance values measured with the photodiode for each trial at each location. Because the luminance was recorded with the EEG system at a digitizing rate of 10 kHz, the temporal resolution was 0.1 ms. To calculate the initial latency, the stimulus onset time was detected as the time point at which the luminance first reached or exceeded 40% of the maximum luminance (with the restriction that the eight consecutive bins just before the onset time bin should be less than 44% of the maximum potential). The initial latency was then calculated as the interval between the stimulus trigger and stimulus onset.

RML1st was defined as the percentage of the maximum luminance of the first frame relative to the maximum luminance over the second and third frames. The maximum luminance was defined differently for different monitors, since the images were displayed continuously for LCD1-OD and LCD2 but displayed in a flash style for CRT and LCD1-ULMB. For the continuously displaying monitors (LCD1-OD and LCD2), the maximum luminance for the first frame was defined as the mean luminance over the first 8.2 ms (corresponding to the duration of a single frame at a 120-Hz refresh rate), whereas the maximum luminance over the next two frames was defined as the mean luminance from 8.3 to 24.9 ms. For the CRT, the maximum luminance was defined as the mean luminance around peaks (0.1 to 0.6 ms, 8.4 to 8.9 ms, and 16.8 to 17.3 for the first, second, and third frames, respectively). For LCD1-ULMB, the maximum luminance was defined as the mean luminance around plateaus (0 to 1.6 ms, 8.3 to 9.9 ms, and 16.7 to 18.3 ms for the first three frames, respectively).

Results

Temporal properties

The temporal characteristics of the monitors are illustrated in Fig. 1. The temporal properties of LCD1-ULMB (the candidate monitor) were evaluated against those of CRT first. In the ULMB mode, the monitor displays images in the flash style like CRTs without reducing the refresh rate. The temporal properties differ between LCD1-ULMB and CRT in that the luminance maintained around the peak (plateau) for a short duration before a quick decrease in LCD1-ULMB, whereas the luminance dropped immediately after reaching the peak in the CRT. The rising times of luminance for LCD1-ULMB and CRT were 1.16 and 1.08 ms, respectively; the falling times of luminance were 0.94 ms for LCD1-ULMB and 2.25 ms for CRT. In LCD1-ULMB, there was a plateau of 1.1 ms between the rising phase and the falling phase. Although the luminance of the CRT rose faster, it dropped more slowly than LCD1-ULMB. On the same monitor, another display mode (LCD1-OD) behaved more similarly to a traditional LCD (LCD2), with the luminance rising slowly and remaining steady for a period before falling, again relatively slowly. The rising times for LCD1-OD and LCD2 were 9.11 and 9.6 ms, respectively, and the falling times were 2.73 and 2.53 ms, respectively. In summary, LCD1-ULMB is similar to CRT in the temporal properties. However, it should be noted that LCD1-ULMB differs from CRTs in that it has a plateau.

RML1st was then analyzed to evaluate how quickly a monitor can reach the maximum luminance. The results showed that the CRT performed excellently in this measurement (Fig. 2). At 120 Hz, it reached about 96.8% (averaged over nine locations) of the maximum luminance in the first frame. The RML1st values were similar across the nine locations of the screen. For LCD1-ULMB, RML1st reached a value of 98.6% for the three top locations, but these values declined for the middle locations (93.7%) and particularly for the bottom locations (79.5%). For LCD1-OD and LCD2, the luminance was rising during the first frame and sustained throughout the second and third frames, exhibiting an RML1st value of 88.3% in LCD2, independent of locations, and values slightly over 90% (90.1% for the top locations, 91.6% for the bottom and middle locations) in LCD1-OD.

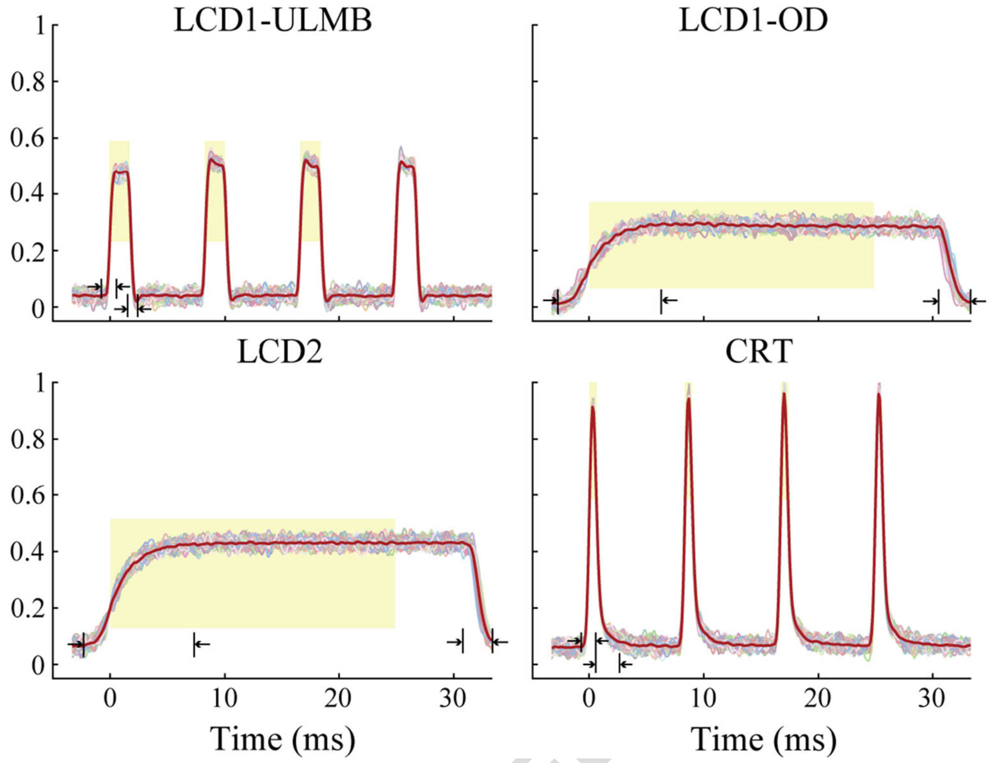

Fig. 1 Mean normalized luminance (solid red lines) and normalized luminance in each trial (lines in unsaturated colors) over time (stimulus onset at 0 ms) for LCD1-ULMB, LCD1-OD, LCD2, and CRT. Luminance was normalized on the basis of the highest luminance of the CRT. Yellow shades indicate the time windows used for calculating the relative maximum luminance of the first frame

Another important temporal property is the initial latency difference across different locations. Generally speaking, CRT had the shortest initial latency, and LCD2 showed the worst performance in this regard (Fig. 3). Most importantly, although LCD1-ULMB had longer initial latencies, the latency values were almost constant across all onset positions, with an average initial latency of 11.25 ms (*SD* = 0.04 ms). This spatial consistency makes LCD1-ULMB perfect for stimulus presentation in studies that require millisecond-level accuracy (Plant, 2016). For example, in event-related potential (ERP) studies, excellent temporal synchrony in stimulus presentation

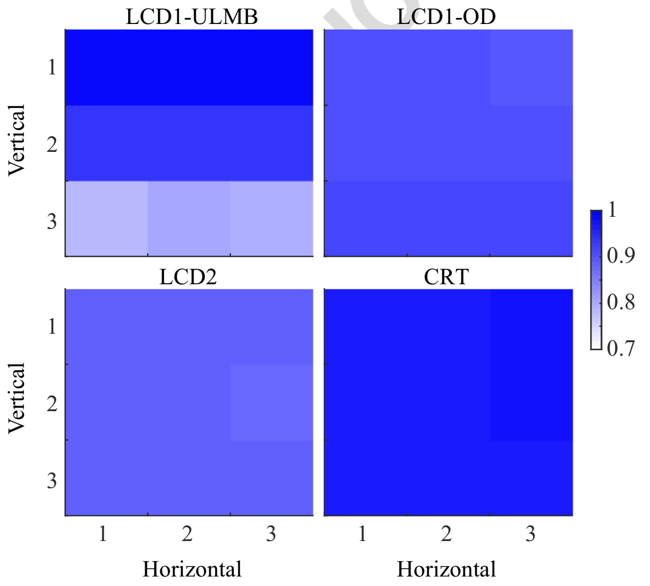

Fig. 2 Relative maximum luminance of the first frame (RML1st) at each location for each monitor. Higher saturation of the color indicates higher RML1st values

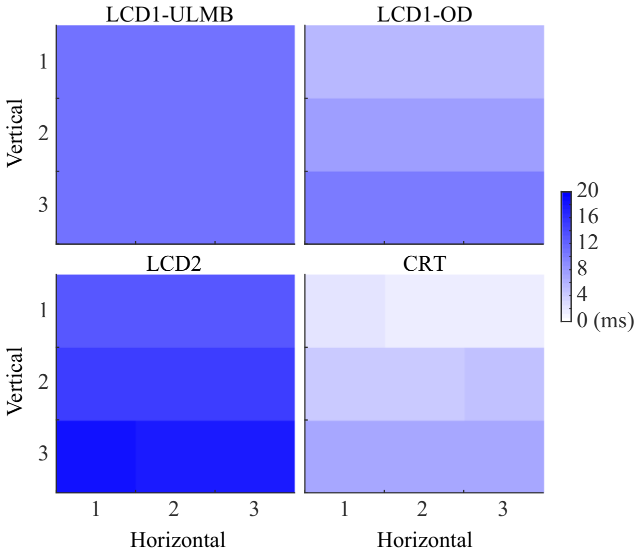

Fig. 3 Initial latencies across locations for the tested monitors, calculated as the interval between the stimulus onset trigger and stimulus onset

(either across different parts of the same stimulus or between different stimuli presented at different locations) will ensure precise time-locking between triggers and the physical onsets of stimulus onsets, thus enhancing the ERP data quality (Luck, 2014). Since CRT presented images with the raster scan beam moving from top to bottom, the initial latency increased accordingly, being shortest at the top left location and longest at the bottom right location (with some variations in the same horizontal line due to the small displacement of the photodiode). LCD1-OD and LCD2 showed the same pattern, with the shortest initial latency at the top (LCD1-OD: 5.58 ms, LCD2: 12.84 ms) and the longest latency at the bottom (LCD1-OD: 10.26 ms, LCD2: 17.99 ms).

Spatial properties

The spatial homogeneity of luminance across different locations on the screen was evaluated. For each monitor, the luminance at each of the nine locations was normalized by the luminance measured at the screen center. Figure 4 demonstrates the luminance variation across locations, showing that the location with the highest luminance differed across monitors. The standard deviations (*SD*s) of the normalized luminance across all nine locations were calculated in order to quantify the homogeneity of spatial luminance. The result showed that LCD1-OD had the largest variation (*SD* = .101), followed by LCD1-ULMB (*SD* = .057) and LCD2 (*SD* = .033), which were similar to the performance of CRT (*SD* = .038).

CRTs are known to present horizontal lines brighter than vertical lines, because the CRTs perform raster scanning horizontally. Since they are not based on raster scanning, LCDs are less affected by this problem (Krantz, 2000; Wang & Nikolic, 2011). To test whether the candidate monitor (LCD1-ULMB) had this issue, in the present study we measured the luminance of different gratings (horizontal, vertical, and oblique) at nine locations. The luminance of the vertical grating and that of the oblique were divided by the luminance of the horizontal grating to measure the normalized luminance relative to the luminance of the horizontal grating (Fig. 5). The results confirmed that, unlike CRT, all tested LCDs showed comparable luminance levels across different orientations. In CRT, the luminance of the vertical/oblique gratings was only about 75.8% of the luminance of the horizontal grating.

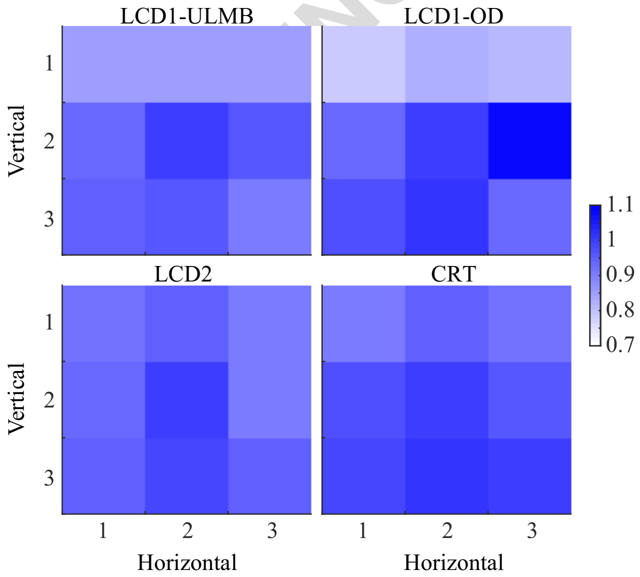

Fig. 4 Normalized luminance relative to the luminance at the central location for each monitor. Higher saturation indicates higher luminance

Viewing angle

For research purposes, ideally, the luminance should be independent of the viewing angle. However, only the CRT met this demand (Fig. 6). For LCD1-ULMB, the measured luminance decreased rapidly as the viewing angle increased. For instance, the measured luminance was only around 51% of the intended luminance at a viewing angle of 45°, a result similar to those from a previous study (Ghodrati, Morris, & Price, 2015; see Fig. 6). These results demonstrated that the tested LCDs showed similar performance regarding the viewing angle, and that the LCD VPixx performed worse than the other two LCD monitors. As a result, researchers should consider controlling for the viewing angle in vision research if stimuli are to be viewed by participants at an angle.

Discussion

Traditionally CRT monitors were used in vision research and were considered the gold standard for visual stimulus presentation. However, it is getting difficult to acquire CRTs in working condition. Thanks to the fast development of the LCD technology, LCD monitors have become the best candidate for replacing CRTs. However, as research suggested, only a few "impulse-type" LCD monitors can meet the technical demands of stimulus presentation. These LCDs are either specially made for vision research (e.g., VPixx ViewPixx 3D Lite and Cambridge Research Systems Display++) or of the new OLED type (e.g., Sony PVM-2541), and thus are not cost-effective and are hard to access. To our knowledge, the only two pulsed consumer-grade LCDs available are the EIZO FG2421 and Samsung 2232RZ. However, the former was reported to have a luminance "bump" in the first white frame when two or more frames of white stimuli were presented (Ghodrati et al., 2015), and the latter mimics impulse-type presentation by adding a black frame after each stimulus frame, and thus reduces its refresh-rate capabilities (Wang & Nikolic, 2011). It was

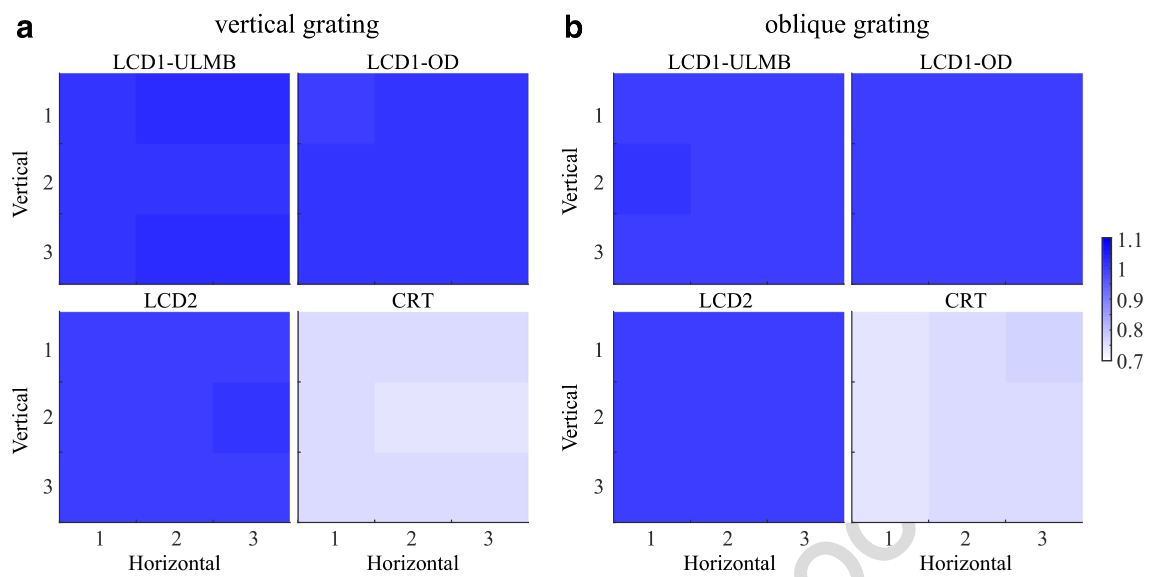

Fig. 5 Normalized luminance of the vertical and oblique gratings as compared to the luminance of the horizontal grating across locations

previously concluded that no consumer-grade LCD could replace CRTs in vision research (Ghodrati et al., 2015). In the present study we successfully addressed this issue by suggesting a consumer-grade LCD (ASUS PG278Q) as a suitable CRT replacement when both time and spatial properties are taken into consideration. When working in an impulse-type mode, this LCD monitor showed consistent initial latencies and reasonable luminance variation across locations.

The impulse-type displays can greatly reduce motion blur, a well-known side effect of hold-type LCDs (Watson & Ahumada, 2010). The ULMB technology was specifically designed to allow LCD monitors to present images in the impulse style. When working in this style, our candidate monitor (LCD1-ULMB) had a rising time comparable to that of a CRT and much shorter than that of a hold-type LCD. However, it should be noted that a luminance plateau (about 1.1 ms) after the peak luminance in the candidate LCD may still cause some motion blur in moving stimuli, an issue that needs attention in visual motion research.

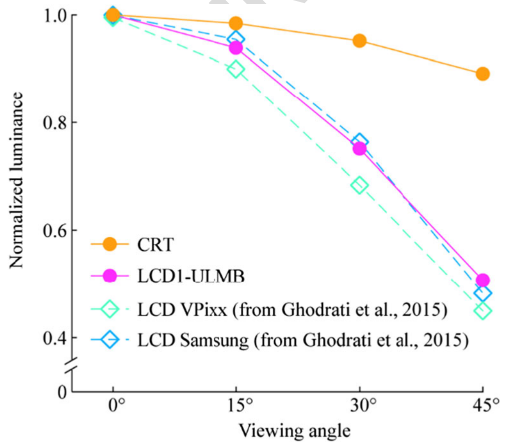

Fig. 6 Normalized luminance at various viewing angles away from 90° (0° indicates a viewing angle of 90°; the larger the viewing angle, the farther away it is from 90°). The results are the averages of five measurements, normalized to the maximum luminance of each monitor measured at 0°. The data for the LCD Samsung and LCD VPixx are from Ghodrati, Morris, and Price (2015)

LCD1-ULMB also satisfied other technical requirements typically demanded in vision research. It showed perfect homogeneity of initial latency across locations, excellent luminance consistency in different orientations, and reliable luminance performance over repetitions. Although LCD1-ULMB has a relatively poor spatial uniformity and the luminance did not reach requested maximum level within the first frame at all locations, those two drawbacks could be effectively corrected with software (e.g., Psychtoolbox). The first issue can be satisfactorily corrected by the method suggested by Cook, Sample, and Weinreb (1993). For the second issue, given the monotonic decrease of RML1st from top to bottom and high consistency over repetitions, the luminance of the first frame can be increased (or, alternatively, decreasing the luminance of the following frames) to achieve equal luminance across frames. After these (spatial and temporal) corrections, LCD1-ULMB showed spatial homogeneity performance superior (*SD* = .017) to that of the CRT (*SD* = .057) (Fig. 7A), and temporal homogeneity performance comparable to that of CRT (it reached 104% of its maximum intensity in the first frame) (Fig. 7B).

In conclusion, the present study has demonstrated that, working in the ULMB mode, an easy-to-find consumer-grade LCD (ASUS PG278Q) is capable of providing a cost-effective solution to accurate visual stimulus

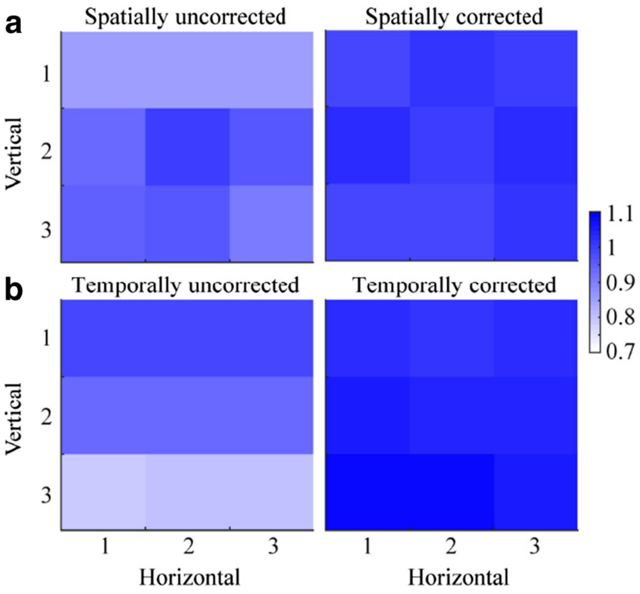

Fig. 7 (A) Spatially uncorrected (left panel) and corrected (right panel) normalized luminance relative to the central locations for LCD1-ULMB. (B) Temporally uncorrected (left panel) and corrected (right panel) RML1st at each location for LCD1-ULMB

presentation. The capabilities of other LCD monitors equipped with the ULMB technology are yet to be determined in future studies. Before employing the solution proposed in this study with a different monitor, a researcher will need to evaluate the monitor following the suggestions from Elze and Tanner (2012).

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