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LCDs are better: Psychophysical and photometric estimates of the temporal characteristics of CRT and LCD monitors

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Abstract Many cognitive and perceptual phenomena, such as iconic memory and temporal integration, require brief displays. A critical requirement is that the image not remain visible after its offset. It is commonly believed that liquid crystal displays (LCD) are unsuitable because of their poor temporal response characteristics relative to cathode-ray-tube (CRT) screens. Remarkably, no psychophysical estimates of visible persistence are available to verify this belief. A series of experiments in which white stimuli on a black background produced discernible persistence on CRT but not on LCD screens, during both dark- and light-adapted viewing, falsified this belief. Similar estimates using black stimuli on a white background produced no visible persistence on either screen. That said, photometric measurements are available that seem to confirm the poor temporal characteristics of LCD screens, but they were obtained before recent advances in LCD technology. Using current LCD screens, we obtained photometric estimates of rise time far shorter (1–6 ms) than earlier estimates (20–150 ms), and approaching those of CRTs (<1 ms). We conclude that LCDs are preferable to CRTs when visible persistence is a concern, except when black-on-white displays are used.

Keywords Stimulus control · Visual perception · Adaptation and aftereffects

Cathode-ray-tube (CRT) displays have been used extensively in vision research because of their superior response times and reduced motion smear, relative to the liquid crystal displays (LCDs) commonly used in homes and offices. To produce an image on a CRT screen, a stream of electrons is shot at a phosphor-coated screen from an electron gun that can be rapidly turned on or off and repositioned. When hit by the electron stream, the phosphor luminesces for a period that varies with the phosphor's characteristics. Some phosphors (e.g., P15) have virtually no persistence; others (e.g., P31) have persistence that can remain visible for several seconds (Di Lollo, Seiffert, Burchett, Rabeeh, & Ruman, 1997). LCD screens are based on a totally different technology: A steady light source positioned behind the screen is blocked by a layer of liquid crystals arranged in a matrix of pixels. The liquid crystals act as switches that allow the passage of light when a voltage is applied to them. The amount of light transmitted varies with the input voltage. Until recently, LCD screens reacted sluggishly to changes in input voltage. Recent advances in LCD technology, however, have improved their temporal characteristics, making them potential candidates for the laboratory.

Kihara, Kawahara, and Takeda (2010) have shown that observers exhibit comparable performance with CRT and LCD monitors on two well-known attentional and perceptual tasks: the attentional blink and metacontrast masking. As the authors noted, however, these results do not necessarily demonstrate that LCDs are suitable for all experimental paradigms. For instance, because of phosphor persistence, CRT images are known to remain visible for some time after the initial image has been turned off (Di Lollo et al., 1997; Groner, Groner, Müller, Bischof, & Di Lollo, 1993). It is possible that LCD monitors will produce similar residual images as a result of a delay in shifting from one liquid crystal orientation to another. These residual images, which we refer to as *display persistence*, were not of critical importance in the paradigms investigated by Kihara et al. because the target stimuli were invariably

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followed by masks that overwrote any lingering persistence on the display screen. On the other hand, residual images are potentially harmful in paradigms that require precise timing of stimulus offset. One of the objectives of the present study was to investigate the duration of display persistence on both CRT and LCD monitors.

Amongst the paradigms in which display persistence is definitely of concern is the Sperling (1960) paradigm, in which an array of items is flashed briefly on the screen, with observers reporting some or all of the items. Display persistence is also of concern in studies of temporal integration of brief successive stimuli (Irwin & Thomas, 2008). A critical requirement in these paradigms is that there be no residual images left on the screen once the stimuli have been turned off. Otherwise, one might falsely attribute correct performance to persistence in the visual system (iconic memory), when in fact it should be attributed, at least in part, to display persistence. In this case, iconic memory would be inextricably confounded with display persistence.

An example of this type of confounding can be seen in a study by Jonides, Irwin, and Yantis (1982). The principal objective was to determine whether two sequential images displayed at different retinal locations, but at the same spatial location, could be integrated so as to be perceived as a single image. In other words, Jonides et al. (1982) were interested in determining whether temporal integration can occur spatiotopically. The stimuli were similar to those used in a study by Di Lollo (1977), in which a square 5×5 dot matrix was displayed with one dot missing at a randomly chosen location. The observers' task was to report the matrix location of the missing dot. To study temporal integration, Di Lollo displayed the matrix at fixation in two brief successive frames of 12 dots each, separated by a variable interstimulus interval (ISI). At short ISIs, the two frames were seen as a single integrated image, and the missing dot could be located with ease. At longer ISIs, the two frames were perceived as temporally segregated, and the task was impossible.

To study spatiotopic temporal integration, Jonides et al. (1982) displayed the two frames of the matrix at the same spatial location but at different retinal locations. This was done by presenting the first frame to one side of fixation, its onset serving as a signal for the observer to shift his or her gaze to that location. The second frame was then displayed at the same location as the first, after a brief ISI during which the screen was blank. In this display sequence, the two frames were in spatial registration but they impinged on different retinal locations. The finding that the location of the missing dot was reported with considerable accuracy was regarded as evidence for spatiotopic temporal integration.

This conclusion, however, was vitiated by a considerations of phosphor persistence. The phosphor used in the Jonides et al. (1982) study was P4, which has been shown to generate visible persistence beyond 1 s in dark-adapted viewing (Di Lollo et al., 1997). Given such long phosphor persistence, the dots in the first frame were still visible when the second frame was displayed. Thus, integration of the two frames was mediated not by a visual memory of the dots in the first frame, but by their actual presence on the screen because of phosphor persistence. This was later confirmed by Jonides, Irwin, and Yantis (1983), who used light-emitting diodes that are free from persistence and found no evidence of spatiotopic temporal integration.

In fairness to Jonides et al. (1982), industrial specifications of decay characteristics indicated that the relative brightness of the P4 phosphor decreases to 1% of maximum within about 0.5 ms (Bell, 1970). This specification seemed to justify the use of P4 phosphor in the Jonides et al. study. The important message is that, as explained below, photometric estimates cannot be used as reliable guides to the visibility of the persistence of a display.

To avoid the type of confound that flawed the study of Jonides et al. (1982), we need to know the time course of the display persistence visible on a screen after the stimulus has been turned off. That is, we need information about the *visibility* of display persistence, as distinct from its *luminance*. The time for which a stimulus continues to luminesce on the screen is typically measured with a photometer. However, such luminance readings do not provide unambiguous measures of visibility. The conversion from luminance values to visibility estimates is complicated by such factors as response compression (Hood & Finkelstein, 1986) and changes in the gain of the visual system arising from rapid neural adaptation. This is an important consideration. Whereas the sensitivity of a photometer is invariant with changes in the luminance of the light source, the sensitivity of the visual system changes rapidly and dynamically with changes in stimulation. The gain of the visual system is known to increase by one log unit within about 100 ms of stimulus offset, and by two log units shortly thereafter (Baker, 1963). For this reason, a stimulus can still be visible shortly after it has been turned off, even though the level of photometrically measured luminance may be regarded as negligible.

Estimates of the visibility—as distinct from the luminance—of display persistence are available for such phosphors as P15 and P31 (e.g., Di Lollo et al., 1997). However, no corresponding estimates are available for the visibility of the persistence of CRT screens commonly used in studies of cognition and perception. The present work provides those estimates.

In the present work, we examined the time course of the visibility of display persistence on both CRT and LCD monitors under light-adapted and dark-adapted viewing. A vertical or horizontal bar was displayed on the monitor behind a closed mechanical shutter. The shutter opened rapidly at varying intervals following the offset of the bar. Therefore, any image still visible on the screen was the result of display persistence. The observers' task was to identify the bar's orientation.

A second, and just as important, objective of the present work was to examine the timing of LCD screens. Previous estimates had revealed LCD displays to be sluggish, requiring as long as 150 ms to reach maximum luminance (Liang & Badano, 2007). This slow rise time rendered LCD screens unsuitable for experiments or applications that require brief displays. A recent advance in LCD technology, known as *overdrive technology*, however, has resulted in substantial reductions in their response times, bringing LCD screens within the range of useful devices.

The principal objective of overdrive technology is to speed the transition from one level of luminance to another, as when a light stimulus is presented on a dark background. Figure 1 illustrates how this is done. Panels a and b show the course of events without overdrive. The two functions in each panel illustrate a shift from a lower level (Level 1) to higher levels (Levels 2 and 3) of intensity. Panel a illustrates changes in the voltages applied to the liquid crystals to achieve and maintain the desired level of luminance. Panel b illustrates the temporal course of the changes in luminance in response to the changes in voltage. Clearly, the sudden increments in voltage (panel a) result in sluggish changes in luminance (panel b). The important thing to note is that the rate of change in luminance is faster for the higher voltage (panel b, segmented line). For example, luminance reaches Level 2 sooner when the voltage is switched to Level 3 than when it is switched to Level 2. This phenomenon is used in overdrive technology to achieve a faster transition between different levels of luminance.

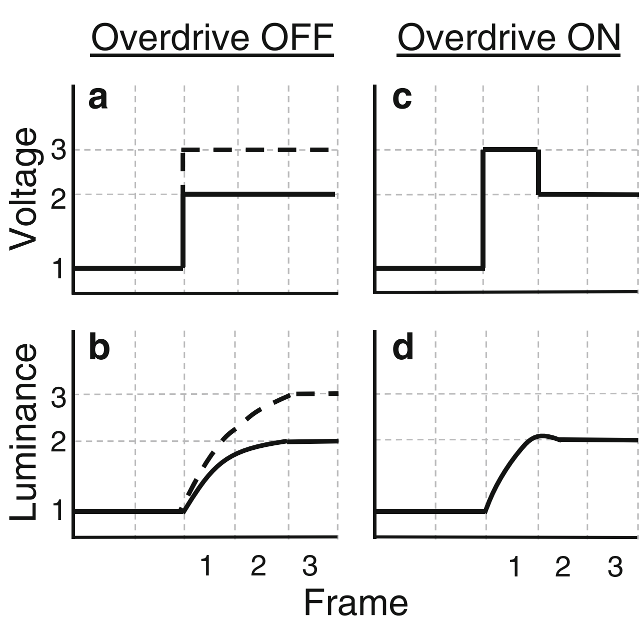

Fig. 1 Schematic representation of the implementation of overdrive technology in LCD monitors. See the text for an explanation

Suppose that the luminance of a stimulus is to be switched rapidly from Level 1 to Level 2. When implementing overdrive, the voltage is initially changed to Level 3 for a single frame, and then lowered to Level 2 (Fig. 1c). The corresponding changes in luminance are illustrated in panel d. Because of the overdrive procedure, the luminance in panel d reaches (and may overshoot) Level 2 within a single frame, as compared to approximately two frames without overdrive (Fig. 1b, solid line). An example of overshoot is seen in Fig. 1d; it occurs when the fast rate of change in luminance associated with the high voltage causes it to exceed the criterial level before the input voltage is reduced to the appropriate level.

Part I: Psychophysical estimates of visibility

General methods

Participants Data were collected from two of the authors (H.E.P.L. and M.R.Y.) and from a third practiced psychophysical observer (V.D.L.). All had normal vision.

Apparatus Stimuli were presented on one of two computer monitors: a 21-in CRT (AccuSync 120 equipped with B22 phosphor, denoted as having "medium-short" persistence, manufactured by NEC: www.necdisplay.com) and a 23-in. LCD (BenQ XL2410T, www.benq.com). B22 phosphor is also known as P22 phosphor. The CRT was set at a resolution of 800×600 pixels and the LCD at 1,920×1,080 pixels. Both monitors operated at a refresh rate of 120 Hz and were switched on at least 30 min before the beginning of the experiment. The brightness and contrast settings of both display monitors were set to maximum, so as to examine the worst-case scenario for both monitors. The luminance of the stimuli under different viewing conditions is specified below.

Observations were made under two lighting conditions: dark, and ordinary room lighting. The corresponding screen luminance values are specified below. In the dark-viewing condition, the screen was encased within a cover that prevented any screen light from escaping the enclosure. The displays were viewed monocularly with the preferred eye through a mechanical shutter with a 25-mm diameter [Gerbrand Model G1166 (D)/(S)]. The shutter opened from the center out as an expanding circle and was positioned over a small hole in the cover 42 cm from the center of the screen. According to the manufacturer's specifications, the shutter changes from closed to open in 2 ms. We checked on this with a photodiode and found that the opening delay was close to specification, and never exceeded 4 ms.

Stimuli The display consisted of a vertical or horizontal light bar presented in the center of a darker background.

At the viewing distance of 42 cm, the bar subtended 3.4º× 13.6º (210×57 pixels in the CRT monitor, 340×90 pixels in the LCD monitor). The orientation of the bar was chosen randomly on each trial, with the constraint that each orientation was chosen an equal number of times.

Procedure Each trial began with a 200-ms display of the bar behind a closed shutter. The shutter opened at varying delays following the offset of the bar. In calculating the shutter delays, we took into account the time required for the raster to travel from the top of the screen to the screen location beyond that occupied by the vertical bar. This was done to ensure that the bar had been removed from the screen before the shutter began to open. Given a refresh rate of 120 Hz, the signal to open the shutter was issued 6 ms after the beginning of the raster scan. This was designated as the 0-ms delay. Longer delays were obtained by adding the appropriate temporal intervals. Because of the shutter-opening time, the actual shutter delays were 2–4 ms longer than those shown in the figures. When the shutter opened, the observer attempted to identify the orientation of the bar on the basis of the display persistence remaining on the screen. A total of 48 responses were collected at each combination of lighting condition, monitor, and shutter-opening delay. Stimulus presentation and shutter control were governed by programs written in E-Prime (Version 2.0; Psychological Software Tools, Pittsburgh, PA).

Dark-adapted viewing

The experiment was conducted in a dark room, and each observer was dark-adapted for at least 30 min prior to the session. The luminance of the white bar on the CRT monitor was 120.0 cd/m^2, and the luminance of the black background was 0.2 cd/m^2, as measured by a Minolta LS-110 luminance meter. The corresponding luminance values for the LCD screen were 242.1 cd/m^2 and 0.2 cd/m^2. The range of shutter-opening delays from stimulus offset was set to encompass identification accuracies from near-perfect to near-chance.

The results for the CRT screen, illustrated in Fig. 2, show that the phosphorescence of the CRT screen remained visible (accuracy above 50%) for over 3 s for all observers. Di Lollo et al. (1997) reported similar estimates for P4 and P31 phosphors. In contrast, the display persistence of the LCD screen was negligible, with accuracy hovering around chance even at a nominal shutter delay of 0 (averaged across the three observers, the percentage of correct responses was 49%). We conclude that under dark-adapted conditions, the LCD screen was superior in producing essentially no display persistence, as compared to substantial persistence for the CRT screen.

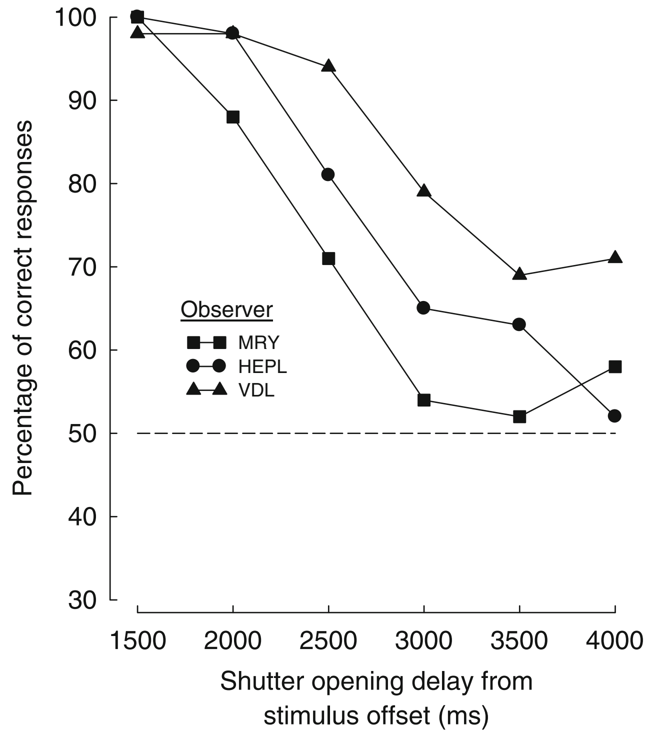

Fig. 2 Dark-adapted viewing of a vertical or horizontal bar displayed behind a closed shutter on a CRT screen: Percentages of correct identifications of the bar orientation as a function of the shutter-opening delay from stimulus offset, displayed separately for the three observers. The dashed line indicates chance level

The above measurements were performed with the brightness and contrast settings of both the CRT and the LCD screens set to maximum. Because these settings resulted in higher luminance for the LCD screen (see above), we replicated the measurements with the luminance of the LCD screen set to match that of the CRT screen. As specified above, the luminance of the CRT was 120.0 cd/m^2 for the white bar and 0.2 cd/m^2 for the black background. The matching values for the LCD screen were 123.1 cd/m^2 and 0.1 cd/m^2, respectively. Averaged across the three observers, the percentage of correct responses obtained at the lower luminance setting for the LCD screen was 52%, which was very similar to that obtained at the higher setting. Phenomenologically, the stimuli were never visible on any trial.

Light-adapted viewing

The procedures here were the same as in dark-adapted viewing, except that the session was conducted under normal room-lighting conditions. The monitor was not covered with a shield, and participants were not dark-adapted prior to the session. The luminance of the CRT monitor was 123.5 cd/m^2 for the white bar and 3.5 cd/m^2 for the black background. The corresponding estimates for the

LCD monitor were 242.6 cd/m^2 for the white bar and 0.8 cd/m^2 for the black background. The results for the CRT screen are illustrated in Fig. 3. As expected, the visibility of display persistence was shorter than in dark-adapted viewing (Fig. 2), reaching chance level approximately 125 ms after stimulus offset. Even such relatively short persistence, however, can be harmful when brief exposures are required as in studies of iconic memory and temporal integration. A notable finding was that when the polarity of the displays was reversed (i.e., a black bar on a white background), no persistence was visible even at the shortest shutter delay (averaged across the three observers, the percentage of correct responses at a nominal shutter delay of 0 was 49%).

The results for the LCD screen revealed no display persistence even at the shortest shutter delay for either white-on-black or black-on-white displays (averaged across the three observers, the percentages of correct responses at a nominal shutter delay of 0 were 47% and 49%, respectively). As was done in the dark-adapted viewing condition, a separate set of

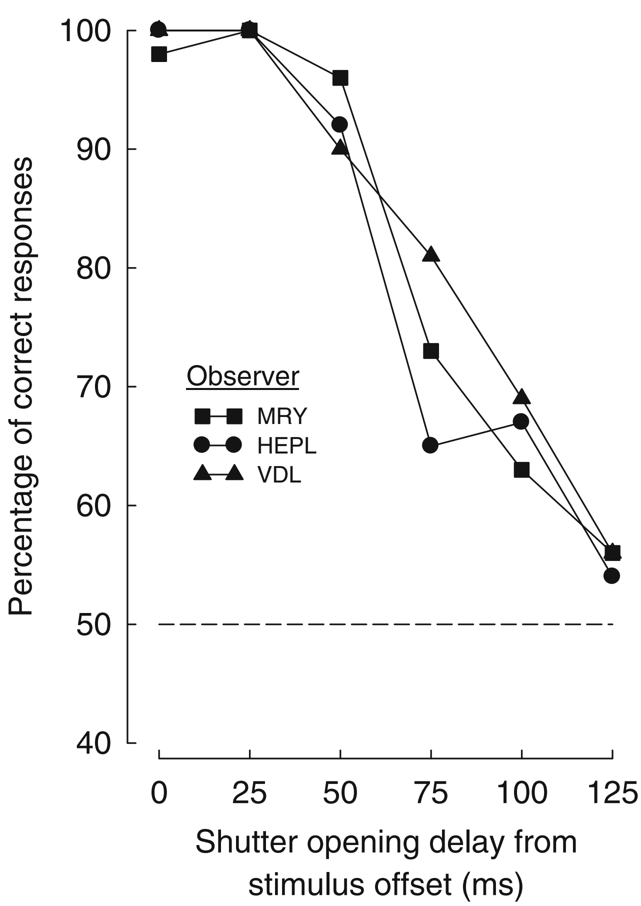

Fig. 3 Light-adapted viewing of a vertical or horizontal bar displayed behind a closed shutter on a CRT screen: Percentages of correct identifications of the bar orientation as a function of the shutter-opening delay from stimulus offset, displayed separately for the three observers. The dashed line indicates chance level

estimates were obtained for the LCD screen with the luminance set to match that of the CRT. As specified above, the luminance of the CRT was 123.5 cd/m^2 for the white bar and 3.5 cd/m^2 for the black background. The matching values for the LCD screen were 124.0 cd/m^2 and 0.9 cd/m^2, respectively. Averaged across the three observers, the percentages of correct responses obtained at the lower luminance setting for the LCD screen were 47% for white-on-black displays and 49% for black-on-white displays. These results were very similar to those obtained at the higher setting. Phenomenologically, the stimuli were never visible on any trial.

Part II: Photometric estimates of luminance

Earlier estimates of the time to reach maximum luminance in LCD screens have ranged up to 47 ms for black-to-white transitions (Wiens et al., 2004) and up to 150 ms for gray-to-gray transitions (Liang & Badano, 2007). Those estimates, however, were obtained before the advent of overdrive technology, which boosts the voltage applied to the liquid crystals, thereby markedly improving the temporal response characteristics of LCD screens. The present photometric measurements were performed to assess the extent to which the response times were improved by overdrive technology.

The monitors and the stimuli were the same as those used for the psychophysical estimates. The luminance of the stimuli was measured with a photo diode (S7686, Hamamatsu Photonics) calibrated for the human spectral sensitivity function (spectral response range 480–660 nm, peak sensitivity 550 nm), with an active area of 2.8×2.4 mm. The photodiode was placed on the center of the screen, and its output was amplified by a Thorlabs PDA200C photo diode amplifier. The signal was sampled at a rate of 25 kHz by a quickDAQ (Version 1.6.0.8) data acquisition system on a laptop computer via a Data Translation DT9804-EC-I USB Data Acquisition Function Module. In preliminary trials, we found that the LCD display reached maximum luminance within a single 8.33-ms refresh frame. To add a margin of safety, each display consisted of two consecutive frames, for a total display duration of 16.7 ms. A total of 100 such trials, separated by 100-ms gaps, were recorded in the data acquisition system. The average of those 100 trials was then smoothed by means of a central-moving-average procedure using 11 data points, 5 on either side of the point whose mean was to be calculated. The measurements were performed in a dimly lit room.

The results for the CRT screen are shown in Fig. 4, which illustrates transitions from black to white for two successive frames. The zero point on the abscissa represents the vertical sync signal initiating the start of the first frame. Because the stimulus was presented in the center of the screen and the

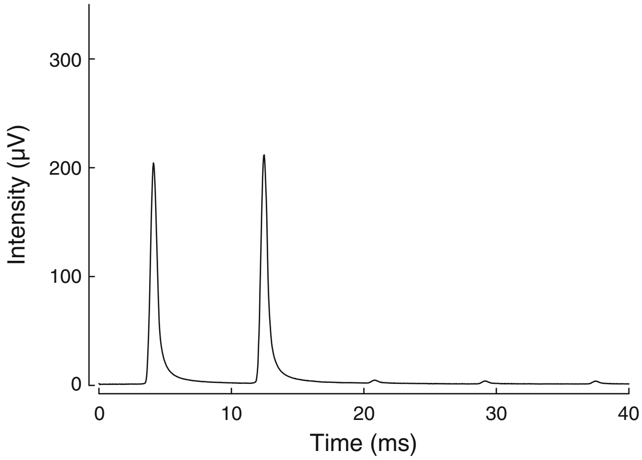

Fig. 4 Luminance changes produced by a white bar displayed for two refresh cycles on a CRT screen running at 120 Hz. Represented on the ordinate is the strength of the illumination signal (in microvolts) recorded by the photodiode

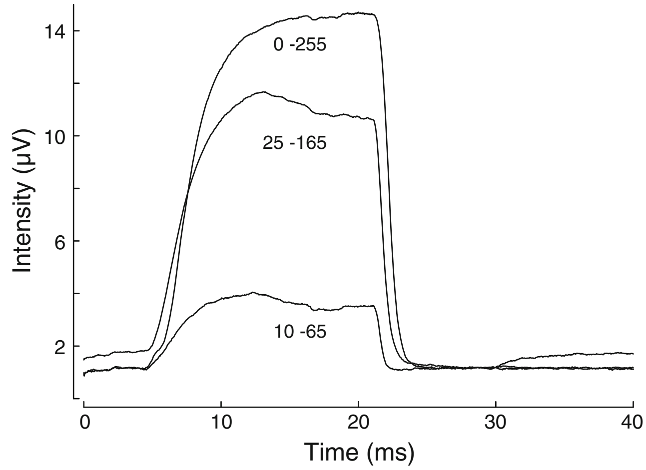

Fig. 5 Luminance changes produced by a light bar displayed for two refresh cycles on an LCD screen running at 120 Hz. Three luminance transitions were tested: one black-to-white transition (RGB 0, 0, 0 to 255, 255, 255, labeled as 0–255), and two gray-to-gray transitions (RGB 25, 25, 25 to 165, 165, 165, labeled as 25–165, and RGB 10, 10, 10 to 65, 65, 65, labeled as 10–65). Represented on the ordinate is the strength of the illumination signal (in microvolts) recorded by the photo diode

plotting rate was 120 Hz (8.33 ms per frame), the onset of the function is delayed by approximately 4.2 ms from the zero point—to wit, by the time it took the raster scan to reach the center of the screen. Using the criteria specified below in Fig. 6, the rise time and fall time of the left-hand function in Fig. 4 were 320 and 480 μs, respectively. These times are similar to those reported by Westheimer (1993) for P31 phosphor. The duration of a single frame, based on the criteria specified in Fig. 6, was 920 μs. It is perhaps worth noting that the small bumps in the function in Fig. 4 starting just after the 20-ms mark are consistent with similar bumps reported by Kihara et al. (2010, Fig. 1b). Since the frequency of these bumps are in phase with the refresh cycle, they are likely to be produced by electrons shot at the screen while the electron gun is held at a subcritical voltage while the screen is nominally black.

The results for the LCD screen are illustrated in Fig. 5. Estimates were obtained for a black-to-white transition (RGB 0 to 255) and for two gray-to-gray transitions (RGB 10 to 65 and 25 to 165). As was the case for the CRT functions (Fig. 4), the LCD functions in Fig. 5 are delayed by approximately 4.2 ms from the zero point. This was to be expected, on the grounds that, just like CRT monitors, LCD monitors operate on a raster-scan system.

The functions in Figs. 4 (CRT) and 5 (LCD) differ substantially from one another in maximum intensity (approximately 200 and 14 μV, respectively). As noted in the Method section, the two screens were set to maximum luminance. This resulted in photometric readings of 120.0 and 242.1 cd/m^2 for the CRT and LCD screens, respectively. The photometric measures illustrated in Figs. 4 and 5, however, exhibit the opposite relationship, with the CRT having the greater intensity. This discrepancy can be understood in terms of the different sampling rates used in the measurements. The luminance values of 120.0 and 242.1 cd/m^2 were obtained with a photometer that averaged the screen output over a period of about 1.5 s (~0.67 Hz), whereas the intensity values in Figs. 4 and 5 were obtained with a light sensor that sampled the output every 0.00004 s (25 kHz). The important consideration is that any given pixel in the CRT screen was activated only once per refresh cycle (see Fig. 4), whereas the corresponding pixels in the LCD screen emitted light continuously. To yield similar time-averaged luminances, therefore, the electron beam in the CRT needed to have a higher intensity relative to the backlight of the LCD screen. This difference in intensity is reflected in the functions in Figs. 4 and 5.

We estimated three parameters for each of the three functions in Fig. 5: rise time, duration, and fall time, as illustrated in Fig. 6. To compute these parameters, we defined the baseline for each function as the average intensity from the beginning of the measurement to 4.2 ms beyond the zero point. Computation of the rise and fall times, however, was complicated, because the overdrive technology caused a brief overshoot of the asymptotic level in each of the three functions. For this reason, rise time was defined as the time taken for the intensity to change from 10% to 90% of the difference between the baseline and the asymptotic intensity, defined as the average intensity over the last 4.2 ms of the display (i.e., the 4.2-ms period starting 16.67 ms from the zero point). Rise times were 3.0, 3.7, and 4.8 ms for the 10–65, 25–165, and 0–255 functions, respectively.

Duration was defined as the difference between the 10% points in the leading and trailing edges of each function. The

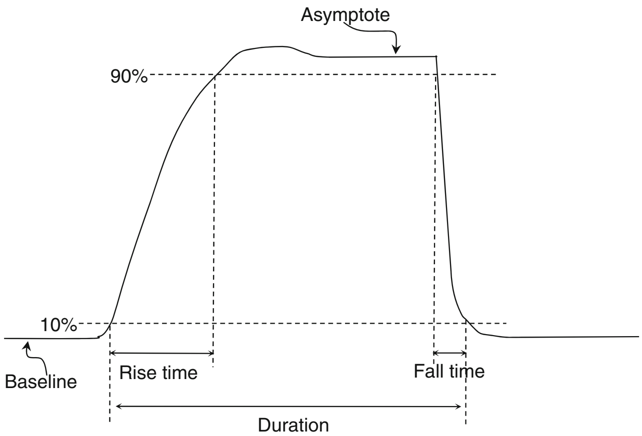

Fig. 6 Schematic representation of the method of calculating the rise time, fall time, and duration of the displays on the LCD screen

estimated durations were 16.9, 17.0, and 17.0 ms for the 10–65, 25–165, and 0–255 functions, respectively. Fall time was defined as the time taken for the intensity to change from 90% to 10% of the difference between the baseline and the asymptotic level. The estimated fall times were 0.6, 1.0, and 1.4 ms for the 10–65, 25–165, and 0–255 functions, respectively.

A taxonomic survey of commercially available LCD monitors was obviously beyond the scope of the present work. To gain some indication of the generality of the findings reported in the foregoing analysis, however, we tested two additional LCD monitors: a Dell 1907FPc (not equipped with overdrive, released February 2006) and a ViewSonic VS12841 (equipped with overdrive, released December 2009). A further reason for testing additional monitors was to ascertain whether the superior temporal characteristics exhibited by the BenQ XL2410T could be ascribed to the implementation of overdrive technology. The three monitors (Dell, ViewSonic, and BenQ) are compared in Fig. 7. The data were collected as described above, with the following exceptions. The stimuli were displayed for 66.7 ms because preliminary results indicated that all of the monitors reached asymptotic level within this time window. The BenQ monitor was refreshed at a rate of 120 Hz (i.e., the stimuli were displayed for eight frames). Because the Dell and the ViewSonic monitors could not reach a frame rate of 120 Hz, they were run at 60 Hz (i.e., the stimuli were displayed for four frames). In addition, the ViewSonic and the BenQ monitors were run with the overdrive feature either ON or OFF. This could not be done with the Dell monitor, which was not equipped with overdrive.

The photometric measurements are illustrated in Fig. 7 and Table 1. Clearly, the response characteristics of both the ViewSonic and BenQ monitors were markedly improved with overdrive turned on. It is also clear that the performance of older models, exemplified by the Dell monitor, is inferior to that of more recent models, even with overdrive in the newer models turned off. All functions in Fig. 7 exhibited some 60-Hz fluctuations, most noticeable in

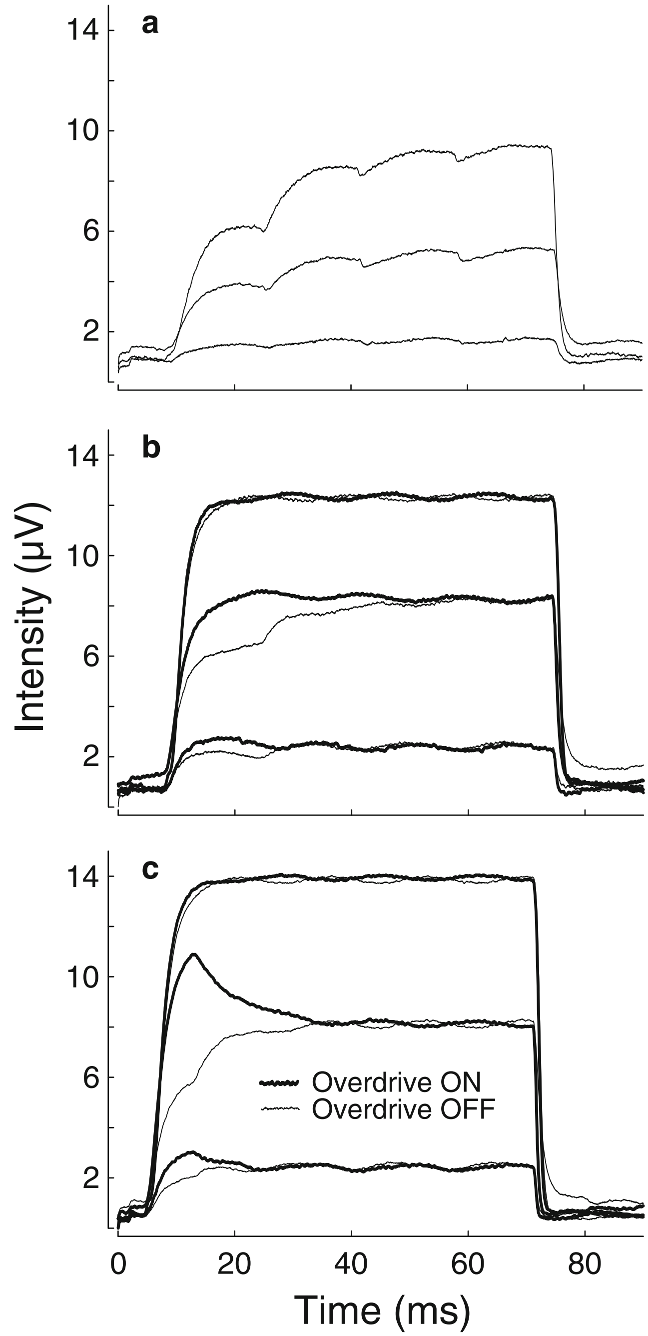

Fig. 7 Luminance changes produced by a light bar displayed for 66.7 ms on three LCD screens. (**a**) Dell 1907FPc, run at 60 Hz; (**b**) ViewSonic VS12841, run at 60 Hz; (**c**) BenQ XL2410T, run at 120 Hz. Three luminance transitions, fully described in the Fig. 5 caption, were tested in each monitor: one black-to-white transition (RGB 0–255) and two gray-to-gray transitions (RGB 25–165 and RGB 10–65). The ViewSonic and the BenQ monitors were tested with the overdrive feature turned ON (bold functions) and OFF (thin functions). Represented on each ordinate is the strength of the illumination signal (in microvolts) recorded by the photo diode

Table 1 Rise times, fall times, and durations (in milliseconds) for the BenQ XL2410T, ViewSonic VS12841, and Dell 1907FPc LCD monitors, for three RGB transitions and with overdrive turned OFF or ON

Monitor RGB Transition		BenQ			ViewSonic			Dell		
		10–65	25–165	0–255	10–65	25–165	0–255	10–65	25–165	0–255
Overdrive OFF	Rise Time	4.04	2.36	2.12	17.96	19.76	5.12	24.52	25.36	23.88
	Fall Time	0.88	4.44	1.08	1.00	4.18	1.36	1.88	2.96	1.72
	Duration	70.80	71.84	68.52	66.96	70.36	67.16	67.48	68.28	66.28
Overdrive ON	Rise Time	3.52	1.12	1.96	2.40	5.96	4.12			
	Fall Time	0.24	0.48	1.04	0.60	1.36	1.40			
	Duration	70.12	67.84	68.44	66.44	67.44	67.16			

Fig. 7a. Similar fluctuations have been reported by Kihara et al. (2010, Fig. 4c) and by Wiens et al. (2004, Fig. 1b). This 60-Hz component is inherent in the LCD power supply and can be much reduced or eliminated by a 60-Hz notch filter on the power cable, by placing the power supply away from the monitor, or by shielding the main LCD circuit board with a sheet of mu-metal.

General discussion and conclusions

The psychophysical estimates are unambiguous: For white images on a black background, the BenQ LCD screen never produced any display persistence, even in dark-adapted viewing, whereas the CRT produced substantial persistence in both light- and dark-adapted viewing. On the other hand, neither monitor produced any measurable visible persistence for black images on a white background. Clearly, when display persistence is a concern, LCD screens are preferable to CRT screens unless the displays consist of black-on-white stimuli.

As compared to photometric estimates obtained with LCD monitors without overdrive or with overdrive turned off (Fig. 7; see also Liang & Badano, 2007; Wiens et al., 2004), the present estimates highlight the substantial improvement in temporal response characteristics brought about by overdrive technology. For example, our estimated rise time of 1–6 ms is considerably shorter than estimates obtained without overdrive (2–25 ms in our estimates, 20–150 ms in past research; Liang & Badano, 2007; Wiens et al., 2004) and approaches that of CRTs (<1 ms). Clearly, recent advances in LCD technology have resulted in a substantial reduction in response times, making LCD screens suitable for presenting brief displays.

Of the many display monitors available commercially, only one CRT and three LCD monitors were selected for testing in the present work. A complete taxonomy of all available monitors would obviously be unfeasible. Alternatively, one might set out to formulate some general rule relating the photometric characteristics of any given monitor to the manufacturer specifications. However, this calculation would be complicated by the fact that manufacturers use different methods and criteria for assessing the temporal characteristics of their displays.

At any rate, knowledge of the temporal characteristics of the display would not provide an estimate of visibility. Ideally, one could attempt to map out the relationship between the photometric estimates of display persistence and the corresponding estimates of visibility. This would provide a look-up table from which the visibility of display persistence could be ascertained from photometric measures. In practice, however, this approach is not viable, because physical measures of light provide only indirect measures of visibility. To be useful in psychophysical experiments, a critical additional step would be required: An estimate of visibility needs to be inferred from the physical measure. Such a conversion is complicated by such factors as response compression (see, e.g., Finkelstein, Harrison, & Hood, 1988) and dynamic changes in the gain of the visual system arising from intensity changes in light input throughout the period of measurement. For example, as noted above, the gain of the visual system is known to increase by one log unit within about 100 ms of stimulus offset, and by two log units shortly thereafter (Baker, 1963). For this reason, a stimulus can still be visible shortly after it has been turned off, even though the level of photometrically measured phosphorescence may be regarded as negligible.

Other considerations in relating visible persistence to physical measures include such factors as the initial luminance of the stimulus, its duration, its visual angle and contrast (Ricco's law), the ambient illumination, and the level of adaptation to that illumination, to name a few. To be clear, even if one were to use a supremely sensitive photometer, the photometric reading would not be an index of visibility: The visibility of the signal could be determined only by means of the kind of psychophysical procedure described in the present work. Perhaps the safest course will be to use the method described in the present work to obtain the required information for the specific display equipment used in any given investigation.

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