26.4: Artifacts of CRT Displays in Vision Research and Other Critical Applications

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Abstract[1]2

Phosphor persistence and video bandwidth affect the appearance of images presented on CRTs. We provide specific illustrations of their effects, revealing severe problems for vision research and other critical applications.

1. Introduction

Images presented on CRTs are widespread in vision research, medical imaging (radiology and microsurgery) and other critical applications. Limited bandwidth, phosphor persistence, limited refresh rate and the interaction of these factors represent limitations that may affect the appearance of images presented on CRTs. The net effect is that the image that is actually displayed on the screen will differ significantly (and sometimes noticeably to the naked eye) from the nominal image, potentially invalidating any conclusions drawn from results obtained in these conditions. This is true even when care is taken to correct for the voltage-to-luminance nonlinearity (gamma function) of the CRT [2] and when the image content lies within the spatial and temporal Nyquist limits.

For instance, in vision research, experiments often require the display of stimuli that are likely to push CRTs beyond their limits, including:

[1] high refresh rates, with interframe intervals shorter than the phosphor decay time. Then, the image that is nominally presented on any give frame merges with residual luminance that is still on the screen from the previous frames.

[2] large and rapid luminance variations along raster lines, well beyond the limits of display bandwidth. Then, pixel luminance "smears" along lines but not across them, potentially resulting in a different appearance for images that only differ as to orientation (vertical vs. horizontal).

We provide specific illustrations of these effects by measuring relevant parameters describing the actual appearance of horizontal and vertical stationary and counter-phase flickering gratings, and we also illustrate the associated problems in vision research by measuring the contrast sensitivity for these horizontal and vertical gratings. As expected, these measurements indicated different sensitivities when the bars of the gratings are parallel and orthogonal to the display raster lines, regardless of the retinal orientation of the gratings. Our results illustrate severe problems with the use of CRTs in vision research, and we discuss related problems in other applications.

2. Methods

Our measurements and results are for an EIZO FlexScan FX· E7 color monitor (P22 phosphor) driven at a frame rate of 122.6 Hz, under the control of VisionWorks (Vision Research Graphics, Durham, NH) software. The monitor was linearized using the standard VisionWorks protocol before any measurements took place, and yielded $r = 0.999997$.

Square-wave and sine-wave gratings were created as 150×150-pixel arrays and displayed in the center of the 1024×600-pixel image area so as to avoid focus problems. The gratings could be horizontal or vertical, had the same nominal mean luminance as the uniform background (34 cd/m^2) and had a range of nominal contrasts. Square-wave gratings were stationary and had a range of spatial frequencies between 2 and 10 pixels/cycle. Sine-wave gratings had a spatial frequency of 30 pixels/cycle and were temporally flickered in square-wave counterphase at rates between 2 and 10 frames/cycle.

All the effects that we are investigating result in differences between the nominal and the actual mean luminances and contrasts of the stimuli. Nominal mean luminance and contrast were set via software, and actual mean luminance was measured with a Minolta LS-100 meter placed at a distance such that the diameter of its circular measuring area was 3/4 the width (or height) of the grating patch. Measurements of the patternless background luminance were interleaved with measurements of grating mean luminance, and covered the same area on the screen.

For psychophysical measurements, the gratings were further windowed with a gaussian with a space constant of 35 pixels so as to eliminate border effects. Subjects sat at a distance of 130 cm so that the spatial frequencies of the gratings (in pixels/cycle) mapped onto the upper range of visible retinal spatial frequencies (in cycles/deg). Thresholds were measured using two forced-choice staircases (3-down/1-up rule; steps down of 0.33 log units; steps up of 0.4455 log units), providing the 83.15 percent-correct point on the psychometric function [1]. Each staircase ran for 20 reversals, only the last 18 of which were used for threshold estimation (average of reversal levels), and the final threshold was computed as the average of the two estimates. Thresholds for horizontal and vertical gratings (on the screen) were measured with the subjects both sitting upright and lying on their sides, so that line raster orientation and retinal grating orientation are not confounded.

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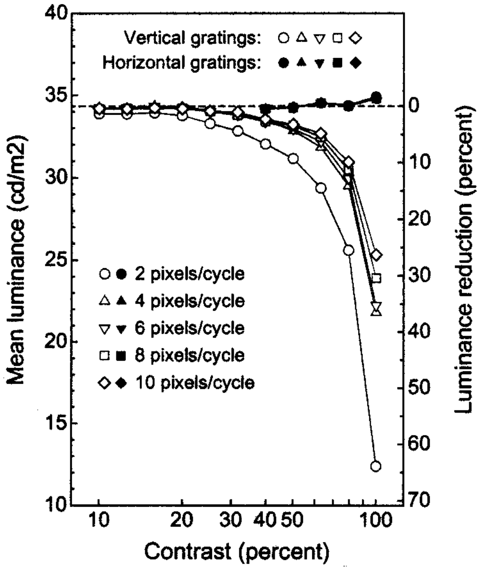

Figure 1. Mean luminance of stationary gratings of several spatial frequencies and orientations (see inset) as a function of contrast. All gratings had the same nominal mean luminance of 34.33 cd/m^2. Symbols represent the average of six measurements; standard deviations were smaller than symbol size. The horizontal dashed line at the background luminance is based on 60 measurements, and the standard deviation was smaller than the width of the line. The scale on the left indicates absolute luminance, while the scale on the right indicates luminance change. Luminance decrements of 1-2% are easily detectable by human observers.

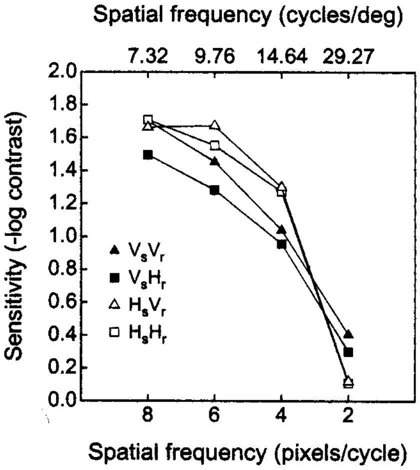

Figure 2. Contrast sensitivity for retinally horizontal and vertical stationary gratings whose bars are oriented either along or across raster lines, as a function of their spatial frequency. V_s: vertical on the screen; H_s: horizontal on the screen; V_r: vertical on the retina; H_r: horizontal on the retina. Note that curves for open symbols (where grating bars are aligned with raster lines) are very similar regardless of whether the gratings turn out to be horizontal or vertical on the retina. The same is true for the curves for filled symbols (where grating bars are orthogonal to raster lines). At the same time, the two pairs of curves differ markedly from each other.

3. Results

3.1 Physical Measurements for Stationary Square-Wave Gratings

Figure 1 shows physical measurements of the mean luminance of horizontal and vertical stationary gratings, as a function of their nominal contrast and parameterized by spatial frequency. Horizontal gratings—with bars oriented along raster lines—are displayed without any distortion of mean luminance. The only exception occurs perhaps at the highest contrast, where mean luminance seems to be slightly higher than elsewhere.

To the casual observer, vertical gratings look just darker than their horizontal counterparts, without any distortion of shape or periodicity. It is as if bright bars were not as bright in the vertical as they are in the horizontal case, while dark bars appear about as dark in both cases.

3.2 Psychophysical Thresholds for Stationary Square-Wave Gratings

Figure 2 shows contrast sensitivity measurements for one observer for eight of the gratings for which data were displayed in Figure 1. There is a clear difference between horizontal and vertical gratings viewed in the upright condition (compare H_sH_r and V_sV_r in Figure 2) that reverses when the subjects lie on their side to break the confounding of grating and raster line orientation. Therefore, it is not the retinal orientation of the gratings that accounts for the different sensitivities, but their orientation with respect to the raster lines of the display.

We believe that it is the open symbols in Figure 2 that purport the true sensitivities to retinally horizontal and vertical gratings, while the filled symbols reflect contamination by CRT artifacts. Yet, variations in mean luminance as a function of contrast (see Figure 1) cannot be held responsible for all of these results: only at contrasts above 10% (for assessing true sensitivities below one) will these artifacts produce an apparent increase in sensitivity, something that shows in our data at the highest frequency (2 pixels/cycle in Figure 2). We believe that the reduced sensitivity observed at 4, 6 and 8 pixels/cycle with vertical (on the screen) gratings has a different source: our display bandwidth may not allow rendering the nominal contrast of these gratings. Although we have no means for measuring the actual contrast of the gratings, our psychophysical data supports this surmise.

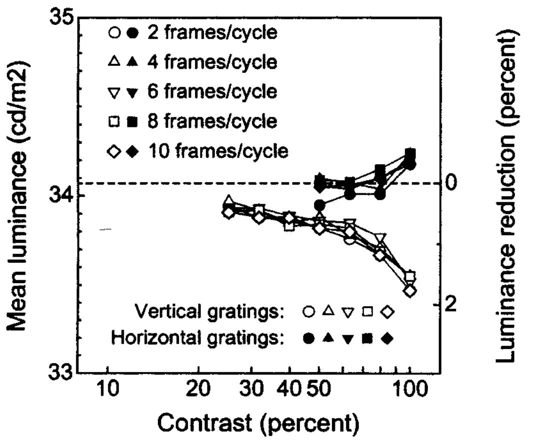

Figure 3. Mean luminance of a 30 pixels/cycle grating flickering in square-wave counterphase at several temporal frequencies and orientations (see inset) as a function of contrast. All gratings had the same nominal mean luminance of 34.07 cd/m^2. Each symbol represents the average of six measurements. The horizontal dashed line at the background luminance is based on 60 measurements.

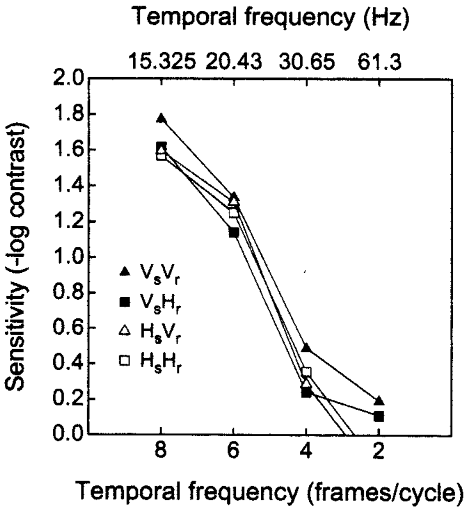

Figure 4. Contrast sensitivity for retinally horizontal and vertical gratings (30 pixels/cycle; 1.95 cycles/deg) whose bars are oriented either along or across raster lines, as a function of temporal frequency of flicker. Acronyms as in Figure 2. Note that the 61.3-Hz flicker is not detectable when the gratings are horizontal on the screen, but becomes detectable (by way of its stationary artifact) when the gratings are vertical on the screen.

3.3 Physical Measurements for Flickering Sine-Wave Gratings

Figure 3 shows measurements of the mean luminance of horizontal and vertical gratings, as a function of their nominal contrast and parameterized by the temporal frequency of flicker. The effects on mean luminance are of the same type as with stationary gratings (compare with Figure 1): horizontal gratings are approximately rendered with their nominal mean luminance while vertical gratings are rendered with reduced mean luminance in a way that depends on their nominal contrast. This effect is much smaller than in the case of stationary gratings (compare the vertical scales of Figures 1 and 3), but the display of these gratings suffers from another artifact: a low-contrast stationary pattern can be observed transparently on the screen, and this pattern is periodic at double the spatial frequency of the grating itself.

With horizontal gratings, this artifact is again a consequence of phosphor persistence: phosphor decay is not fast enough to keep up with the rapid nominal change from bright to dark at the peaks of the grating, resulting in an overall increase in luminance. With vertical gratings, this same effect occurs, but the limited display bandwidth produces an additional artifact which shows in a different general appearance of horizontal and vertical gratings. Although we cannot measure the luminance profile of these artifactual patterns, we next describe the results of psychophysical measurements that clearly reveal their presence.

3.4 Psychophysical Thresholds for Flickering Sine-Wave Gratings

Figure 4 shows contrast sensitivity measurements for one observer for eight of the gratings in Figure 3. Overall, there are no meaningful differences between horizontal and vertical gratings—whether on the screen or the retina—with one remarkable exception: flicker at 61.3 Hz is not visible when the gratings are horizontal on the screen (open symbols), but it becomes visible when the gratings are vertical on the screen (filled symbols). In this latter case, it is not the flicker itself that becomes visible but the stationary artifact. The artifact is also present at other flicker rates, but its low contrast (indirectly indicated by the low sensitivity at the nominal flicker rate of 61.3 Hz in Figure 4) does not interfere with the measurements of flicker sensitivity *per se* in cases where this sensitivity is high.

4. Discussion

On a calibrated color CRT with the conventional P22 phosphor, stationary gratings that nominally differ only as to orientation (vertical or horizontal) turn out to differ enormously as to mean luminance (and, possibly, contrast), and the same is true for counter-phase flickering gratings. In the latter case, high-frequency flicker (still below the Nyquist limit determined by the refresh rate) results in the spurious appearance of a stationary pattern on the screen, whose contrast is sufficiently high to be detected when the nominal stimulus (a flickering grating) is not perceived.

4.1 Artifacts in Vision Research

The effect of orientation on sensitivity to stationary gratings (see Figure 2) could have significant impact on various results reported in the literature, as many studies have used gratings with spatial resolutions (in pixels/cycle) and contrast levels within the range where CRT artifacts will come into play. For example, Polat and Sagi [5] studied the facilitation caused by flanking gratings of high contrast on the detection of a target grating. They compared horizontal and vertical gratings (on the screen) and their gratings had 4 pixels/cycle. The effect of display bandwidth can also account for other results obtained with vertical gratings on the screen. Peli [4] reported that contrast sensitivity for high spatial frequencies was higher when measured at a short observation distance (which implies few pixels/cycle) than it was when measured from a farther distance. We can now conclude that a change in mean luminance at high contrasts (as described by our measurements in Figure 1) was indeed responsible for the apparently higher sensitivity at the shorter distance: it was not the pattern but the spurious change in luminance that the subjects detected well before they could have detected the gratings.

4.2 Artifacts in Stereo and Image Fusion Applications

CRT based field-sequential-stereoscopic displays using LCD or any other shutters suffer from an interocular cross talk due to phosphor persistence even if the shutter is ideal. The amount of cross talk depends on the color of the image (different phosphors have different decay times) and on vertical position on the screen (more cross talk at the bottom of the screen than at the top). The cross talk may affect perceived image quality and visual comfort [6]. Field-sequential-stereo systems can also be used in image comparison experiments (presenting one image to each eye [4]) and image fusion experiments (combining two images by presenting them in the two sequential fields for direct view without a shutter). In these situations, residual luminance may significantly affect the actual image as compared to the nominal image: the cross talk can be as large as 8.5% on our system. A sharp image of this magnitude, when superimposed on a blurred image, may significantly alter its appearance. All this suggests that a display with a 120-Hz refresh rate and no persistence will find use in many applications in which motion stereo or image fusion are needed.

5. Acknowledgements

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