Spatial Vision, Vol. 14, No. 2, pp. 201–215 (2001)

Luminance artifacts of cathode-ray tube displays for vision research

MIGUEL A. GARCÍA-PÉREZ [1,*] and ELI PELI [2]

[1] *Departamento de Metodología, Facultad de Psicología, Universidad Complutense, Campus de Somosaguas, 28223 Madrid, Spain*

[2] *The Schepens Eye Research Institute, Harvard Medical School, 20 Staniford Street, Boston, MA 02114, USA*

Received 8 August 2000; accepted 20 October 2000

Abstract—Phosphor persistence, video bandwidth, DC restoration and high-voltage regulation affect the appearance of images presented on cathode-ray tubes (CRTs), potentially resulting in differences between nominal and actual stimuli. We illustrate these effects by measuring physical parameters of horizontal and vertical static and counter-phase flickering gratings, and we illustrate problems for vision research by measuring contrast sensitivity to these gratings. We also measured the extent to which calibration protocols actually result in the monitor being calibrated over its entire area regardless of image size. The results of our physical measurements indicate substantial differences between gratings that nominally differ only as to orientation. Consistent with these differences, our psychophysical measurements indicate different sensitivities when the bars of the gratings are parallel or orthogonal to raster lines, regardless of the retinal orientation of the gratings. The results of our calibration check show that only a small region around the target area of calibration can be regarded as effectively linearized, and only if the size of the test image used during the check is similar to the size of the calibration patch. Overall, our results indicate potentially severe problems with the use of CRTs in vision research, and we discuss some published results that are likely to have been affected by these problems.

1. INTRODUCTION

Cathode-ray tubes (CRTs) have become the *sine qua non* of experimental vision research. Video bandwidth, DC restoration, high-voltage regulation, phosphor persistence and refresh rate represent limitations that affect the appearance of images presented on CRTs. The net effect of all these factors is that the actual image on the screen may differ significantly from the nominal image, even when

*To whom correspondence should be addressed. E-mail: miguel@psi.ucm.es

care is taken to correct for the voltage-to-luminance non-linearity (gamma function; Peli, 1992) and when the image content is within the Nyquist limits. Vision research experiments often require the display of stimuli that are likely to push CRTs to their limits, including:

1. High refresh rates, with frame duration shorter than phosphor decay time. Then, the nominal image presented on any given frame merges with residual luminance from the previous frame.
2. Large and rapid luminance variations along raster lines, beyond the capabilities of the hardware. Then, pixel luminance 'smears' along raster lines but not across them, potentially resulting in a different appearance of images that nominally differ only as to orientation.

Vision scientists are well aware of these potential problems, as demonstrated by a variety of empirical measurements and discussions published in vision journals (for a review, see Bach *et al.*, 1997). The single aspect that has received the most attention is phosphor persistence, with emphasis on the inadequacy of physical measures of phosphor decay as an index of its perceptual consequences (Groner *et al.*, 1993; Westheimer, 1993, 1994; Di Lollo *et al.*, 1994, 1997; Irwin, 1994; Wolf and Deubel, 1997). The terms of that discussion make conclusions applicable only to the case of static stimuli with sharp offsets.

The effects of phosphor persistence will be larger with time-varying stimuli. For simplicity, consider a full-contrast square-wave grating that flickers in square-wave counter-phase with a two-frame period, and which is displayed at a frame rate of 120 Hz (8.33 ms per frame). To display this stimulus, pixels that are bright on one frame will have to turn dark for the next, and vice versa. With phosphors that leave a luminance residue as large as 4% after 20 ms (see Wolf and Deubel, 1997, their Fig. 4), the required transition from bright to dark will not be achieved in the available time. Conversely, the transition from dark to bright will not be affected by luminance residues. This asymmetry will alter the mean luminance and contrast of the grating, something that will contaminate contrast sensitivity measurements. Of course, gratings flickering at this extreme rate are rarely used in vision research, but frame alternation at this rate is the basic trick for the display of multi-component gratings (e.g. plaids) or other complex stimuli.

One other issue that has been discussed (Pelli, 1997) but does not seem to have been thoroughly studied empirically (but see Mulligan and Stone, 1989; Klein *et al.*, 1996; Lages, 1998) is the effect of horizontal as compared to vertical interactions. If both types of interaction were identical, static gratings would appear identical whether they are displayed vertically or horizontally. Yet, the design of CRTs is prone to much larger horizontal than vertical interactions.

Another consequence of the design of CRTs is that the luminance of a nominally homogeneous field depends on its size on the screen, and is further subject to variations across the face of the monitor (Pelli, 1997). Metha *et al.* (1993) reported that corner luminance is only 73% that at the center of a BARCO CDCT 6551 monitor. These variations may have implications for the display of large stimuli but they also have subtler consequences. Calibration for gamma correction is performed by placing a photometer immediately next to the monitor, thus covering an extremely narrow field. If spatial variations in luminance are proportional to nominal luminance, then all areas of the monitor can be regarded as calibrated as far as linearity is concerned. But if the magnitude of these variations is luminance-dependent, then stimuli displayed off the center of the monitor will not be calibrated. This characteristic may affect experiments involving measurements of contrast thresholds for central patterns in the presence of peripheral patterns, or experiments involving the matching (e.g. as to contrast) of stimuli displayed on different locations.

Here we illustrate the effects just discussed by measuring physical and psychophysical parameters describing the appearance of stimuli displayed on CRTs. Overall, our results illustrate potentially severe problems with the use of CRTs, and we discuss some published experimental results that are likely to have been affected by these problems.

2. METHODS

2.1. Stimuli and apparatus

Our main physical and psychophysical measurements and results are for an EIZO FlexScan FX·E7 color monitor (P22 phosphor) at a frame rate of 122.6 Hz, under the control of VisionWorks™ (Swift *et al.*, 1997). The monitor was calibrated with the standard VisionWorks protocol, and yielded $r = 0.999996$ between measured and nominal luminances. This monitor renders pixels that have a 1 : 1 aspect ratio. We also made physical measurements on a similarly calibrated Image Systems M21L monochrome monitor (DP-104 phosphor; $r = 0.999999$) at a frame rate of 140.8 Hz. However, this latter monitor renders pixels that have a 2 : 3 aspect ratio, which is inappropriate for our psychophysical measurements (see below). All stimuli were monochrome.[1]

P22 is the standard phosphor on color monitors, consisting of R, G and B components which decay to 10% peak emission in 1.5, 6 and 4.8 ms, respectively (Sherr, 1993, Table 2.1). DP-104 is a modified yellow P4 phosphor which decays to 10% peak emission in ~100 μs (manufacturer's specifications).

Besides uniform fields (see below), stimuli were square- and sine-wave gratings created as 150 × 150-pixel arrays and displayed in the center of the image area (1024 × 600 pixels and 40 × 23.4 cm on the color monitor; 1024 × 512 and 27.5 × 21 on the monochrome). The gratings could be horizontal or vertical on the monitor and had the same nominal mean luminance as the nominally uniform background (34 cd/m^2 on the color monitor; 55 cd/m^2 on the monochrome). Square-wave gratings were static and had spatial periods between 2 and 10 pixels. Sine-wave gratings had a spatial period of 30 pixels and flickered temporally in square-wave counter-phase with periods between 2 and 10 frames. Because spatial period is defined in pixels and gratings were horizontal and vertical, a 1 : 1 aspect ratio is crucial for a comparison of visual sensitivities: with other aspect ratios, changes of orientation also result in changes of retinal frequency (in c/deg). For psychophysical measurements all gratings were windowed with a gaussian with a space constant of 35 pixels (0.77 deg at a viewing distance of 130 cm).

Stimuli for the assessment of spatial variations in luminance were uniform fields of a range of nominal luminances between 5 and 100% of the maximal luminance achievable on the monitor. The size of these fields was either the entire image area of the monitor or a central area half the width and half the height of the available image area. In the latter case, the surrounding image area was dark (illustrations are given in Fig. 5 below). Actual mean luminance was measured with a Minolta LS-100 luminance meter.

2.2. *Procedure for physical measurements*

The room was dark and all measurements in a given session took place at least an hour after the monitor had been turned on. This warm-up period guaranteed steady-state operation, which was corroborated by the fact that measurements at the beginning and at the end of each session (separated by over two hours) yielded similar readings.

The luminance meter was mounted on a tripod and placed at a distance such that the diameter of its nominal measuring field — which covers an angle of 1 deg — was 3/4 the width of the grating patch. Gratings were displayed in a random order, and six consecutive measurements of their mean luminance were taken. Measurements of the actual luminance of the uniform background were taken throughout the session in the intervals between presentation of gratings. The six readings for each grating at each contrast were averaged, and so were all measurements of background luminance along the session.

For measurements involving uniform fields, the meter was similarly placed and aimed at eight additional locations on the monitor, away from the center along the eight major cardinal directions and always 3 cm away from the edge of the field. Luminance fields were displayed in a random order and measurements were taken first at the center, then above it, and clockwise thereafter. Six rounds of measurements were taken before changing nominal luminance.

2.3. *Procedure for psychophysical measurements*

Subjects sat 130 or 65 cm away from the warmed-up monitor. Natural pupils were used, and viewing was binocular (subjects FVM and AKN) or monocular with the non-astigmatic eye (subject MAG).

Detection thresholds were measured using 2AFC 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 (García-Pérez, 1998). Each staircase started at maximal contrast and ran for 20 reversals, only the last 18 of which were used for threshold estimation (average of reversal levels). Each trial consisted of two 500-ms intervals signaled by tones of different pitch and separated by 250 ms. Contrast was linearly ramped on and off over 125 ms. The experiment was self-paced, as the next trial did not start until the subject had responded. A small cross served as a fixation mark, which was displayed only during the idle periods between 2AFC trials.

In each session, staircases were interwoven for four stimuli varying only as to spatial frequency (in sessions for static gratings) or temporal frequency (in sessions for flickering gratings). Thus, there were four sets of stimuli: static vertical gratings, static horizontal gratings, flickering vertical gratings and flickering horizontal gratings, where vertical and horizontal refer to orientation on the monitor. In separate sessions, the subjects were sitting upright or lying flat on their sides, so that raster orientation and retinal orientation are not confounded. All subjects completed two sessions of each type (stimulus set by postural position), and the final threshold for each stimulus was computed as the average of the two estimates.[2]

2.4. Subjects

Two naïve subjects and an author participated in the psychophysical experiments. All subjects were experienced observers and had normal or corrected-to-normal vision.

3. RESULTS

3.1. Physical measurements for static gratings

Figure 1 shows the results of physical measurements of the actual mean luminance of horizontal and vertical static gratings, as a function of their nominal contrast. In both CRTs, horizontal gratings (with bars oriented along raster lines; open symbols) are displayed without distortion of their nominal mean luminance, except perhaps on the monochrome monitor where actual mean luminance is slightly lower than nominal. In both CRTs, inaccuracies in the rendition of the mean luminance of horizontal gratings are independent of spatial frequency.

Conversely, the actual mean luminance of vertical gratings (solid symbols) is severely affected by the spatial frequency and nominal contrast of the grating. Only at nominal contrasts below about 20% can the nominal mean luminance be rendered, and at contrasts higher than 50% the reduction in luminance is severe (more than 5%) even for gratings with periods of 10 pixels.

Upon inspection of vertical and horizontal gratings displayed side by side, vertical gratings look darker than their horizontal counterparts, without any distortion of shape or periodicity. Although we could not measure the luminance of each of the individual bars making up the gratings, we suspect that the variations in mean luminance documented in Fig. 1 are accompanied by a mismatch between the

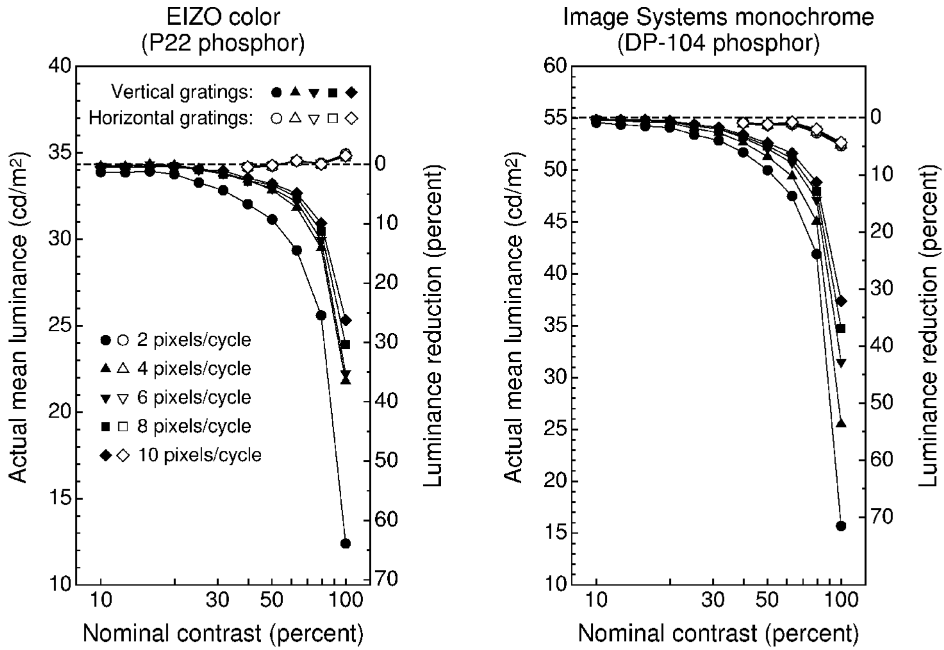

Figure 1. Actual mean luminance of static gratings (see inset legend) as a function of nominal contrast. All gratings had the same nominal mean luminance of 34 cd/m^2 (on the color monitor; left panel) or 55 cd/m^2 (on the monochrome; right panel). Each symbol is the average of six measurements; standard deviations were smaller than symbol size. The horizontal dashed line indicates the actual luminance of the homogeneous background, and is based on 60 measurements.

nominal and actual contrast of the gratings. If the reason that vertical gratings have a lower-than-nominal mean luminance is that their bright bars cannot be rendered at the required luminance while the dark bars are still about as dark as they should be, then actual contrast will also be lower than nominal. We further suspect that in some of the conditions in Fig. 1, where no major difference is observed between nominal and actual luminance, there are still differences (which we cannot assess directly) between actual and nominal contrast. The plausibility of this suspicion is corroborated by the psychophysical results described next.

3.2. Psychophysical sensitivity to static gratings

Figure 2 shows contrast sensitivity measurements for eight of the gratings in Fig. 1. Data from all subjects reveal a clear difference between horizontal and vertical gratings (on the screen) viewed upright: sensitivity in the $H_s H_r$ condition (open squares) is higher than in the $V_s V_r$ condition (solid triangles) at 4, 6 and 8 pixels/cycle, and lower at 2 pixels/cycle. This pattern reverses when the subjects lie on their side to break the confounding of grating and raster orientation (solid squares and open triangles). Thus, sensitivity is not determined by retinal orientation but by orientation with respect to raster lines.

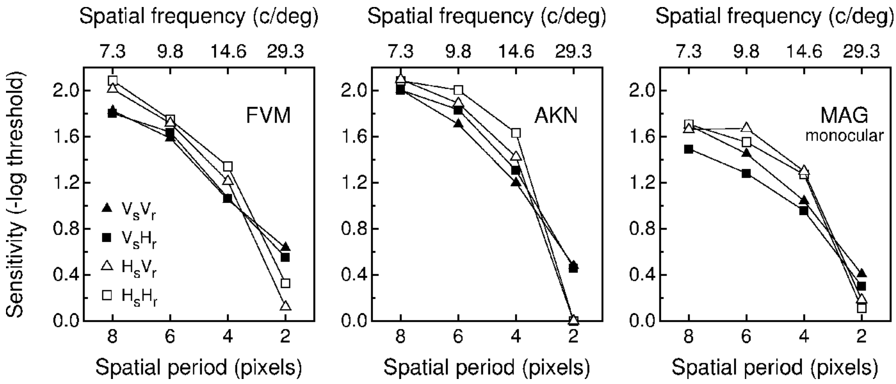

Figure 2. Contrast sensitivity for retinally horizontal (H_r) and vertical (V_r) static gratings with bars oriented horizontally (H_S) or vertically (V_S) on the screen, as a function of spatial frequency. Note that curves for open symbols (H_S, with grating bars along raster lines) are similar regardless of retinal orientation. The same is true for curves for solid symbols (V_S, grating bars orthogonal to raster lines). At the same time, the two pairs of curves differ from each other.

We believe that it is the open symbols in Fig. 2 (for gratings that are horizontal on the screen) that purport the true sensitivity to retinally horizontal and vertical gratings, whereas solid symbols reflect contamination by, at least, luminance artifacts: according to Fig. 1, significant luminance artifacts (say, a luminance reduction of at least 2%) occur at nominal contrasts above 10% for gratings with 2 pixels/cycle, and above 30% for the rest of the gratings. Thus, the apparently higher sensitivity to vertical gratings with 2 pixels/cycle as compared to the same gratings displayed horizontally could be a result of detection of the luminance reduction that occurs before the grating is displayed with a visible contrast. All subjects indeed indicated that on occasions they identified the interval where the stimulus had been presented because of a noticeable change in luminance, not because they had seen any pattern. A similar scenario was described by Artal *et al.* (1995).

Yet, the above argument cannot explain the reduced sensitivity to vertical gratings with 4, 6 and 8 pixels/cycle (compare solid and open symbols in the panels of Fig. 2): in these cases, true sensitivity (as revealed again by the data for horizontal gratings) is outside the range of contrasts where luminance artifacts will occur. We believe that this apparent reduction in sensitivity has its origin in a mismatch between the nominal and the actual contrast of vertical gratings, a mismatch in the direction of actual contrast being lower than nominal.

3.3. Physical measurements for flickering gratings

Figure 3 shows measurements of the actual mean luminance of flickering gratings, as a function of nominal contrast. The effects are of the same type and direction as with static gratings (compare with Fig. 1): horizontal gratings are approximately rendered with their nominal mean luminance while vertical gratings are rendered with reduced mean luminance. This effect is weaker than in the case of static

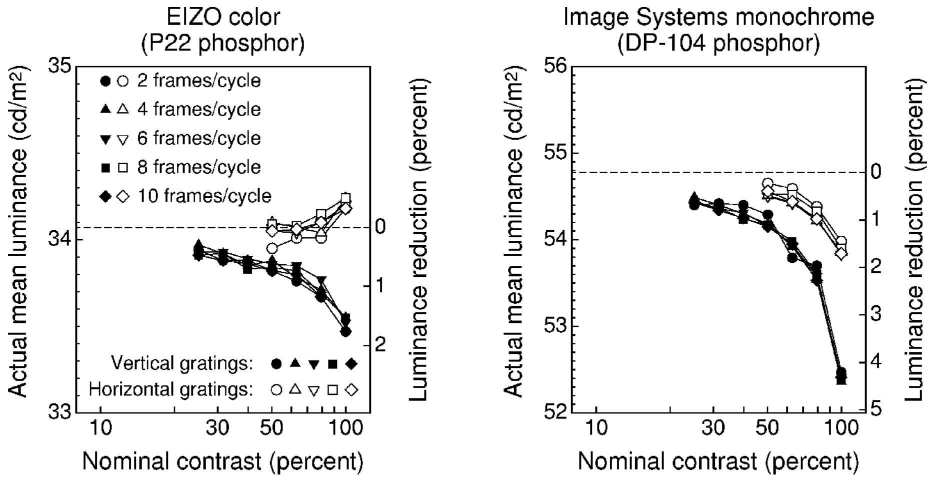

Figure 3. Actual mean luminance of 30-pixels/cycle sine-wave gratings flickering in square-wave counter-phase (see inset legend) as a function of nominal contrast. All gratings had the same nominal mean luminance of 34 cd/m^2 (on the color monitor; left panel) or 55 cd/m^2 (on the monochrome; right panel). Each symbol is the average of six measurements. The horizontal dashed line indicates the actual luminance of the homogeneous background, based on 60 measurements.

gratings (compare the vertical scales of Figs 1 and 3), but the display of these gratings suffers from another artifact: a low-contrast static pattern can be clearly observed transparently on the screen, and this pattern is periodic at double the frequency of the grating itself. This artifact is caused by phosphor persistence: luminance does not change over frames at the mean-luminance crossings of the sine-wave grating, but the temporal alternation of luminance at the peaks/troughs of the flickering sine wave yields a luminance residue that is constant over time and stays static on the screen. In addition, the artifact shows an orientational effect: the pattern has a higher apparent contrast when the grating is vertical on the screen.

3.4. Psychophysical sensitivity to flickering gratings

Figure 4 shows contrast sensitivity measurements for eight of the gratings in Fig. 3. Overall, there are no meaningful differences between horizontal and vertical gratings — whether on the screen or the retina — with a remarkable exception for flicker at 61.3 Hz: the flicker itself is not visible, but the artifact that it produces results in a spurious sensitivity to vertical gratings (where the artifact has more contrast; solid symbols) and a lower or null sensitivity to horizontal gratings (open symbols). The artifact is also present at other flicker frequencies, but its low contrast does not contaminate sensitivity measurements.

3.5. Physical measurements of spatial variations in luminance

The top panels in Fig. 5 show the relative mismatch between actual and nominal luminance at each of nine locations on each monitor, as a function of nominal lumi-

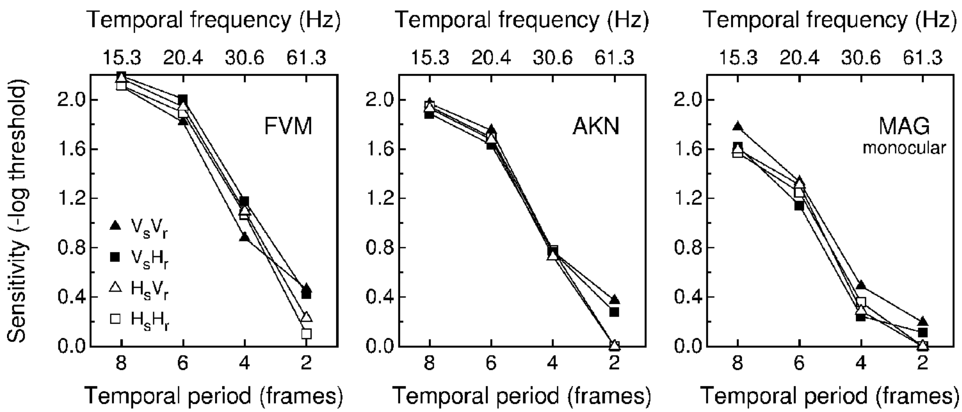

Figure 4. Contrast sensitivity for retinally horizontal and vertical gratings with bars oriented along or across raster lines, as a function of temporal frequency of flicker. The retinal frequency of the 30-pixels/cycle grating was 1.95 c/deg for MAG (at the viewing distance of 130 cm) and 0.98 c/deg for AKN and FVM (at 65 cm). A shorter viewing distance — which does not affect temporal frequency — was used by the latter two subjects in order to reduce the relative amplitude of microsaccades resulting from unstable fixation, which may bring into visibility high-frequency flicker that is otherwise unresolvable (García-Pérez and Peli, 2000). Acronyms as in Fig. 2.

nance. Relative luminance mismatch is defined as 100×(actual-nominal)/nominal so that negative and positive values respectively indicate deficit and excess luminance. Note that a horizontal line purports a constant percent excess or deficit which does not affect contrast, while non-horizontal lines (or segments) indicate mismatch patterns that will affect contrast. Quite notably, both CRTs can be regarded as linearized at all positions, although the monochrome monitor is clearly better. In both cases, there are differences across positions as to the luminance that can be rendered, and the color monitor exhibits a noteworthy non-proportional mismatch at nominal luminances below 20% maximal. This drop occurs at all spatial locations, and may be the result of a parametric algorithm that minimizes absolute residuals.

The calibration check just described applies to the condition indicated in the inset on the top panels of Fig. 5, namely, a central test field that is half as wide and tall as the image area allows. This is precisely the size and location of the field that VisionWorks™ uses during the calibration process. Since many experiments require a larger image area, it becomes crucial to determine how calibration performed with luminance patches of this size carries over to larger patches. The bottom panels of Fig. 5 show results obtained with test fields that cover the entire image area. Quite clearly, a calibration protocol carried out with small patches does not guarantee calibration for larger patches. Each CRT exhibits a different pattern of miscalibration that further varies with spatial position, but all patterns are equally unfit.

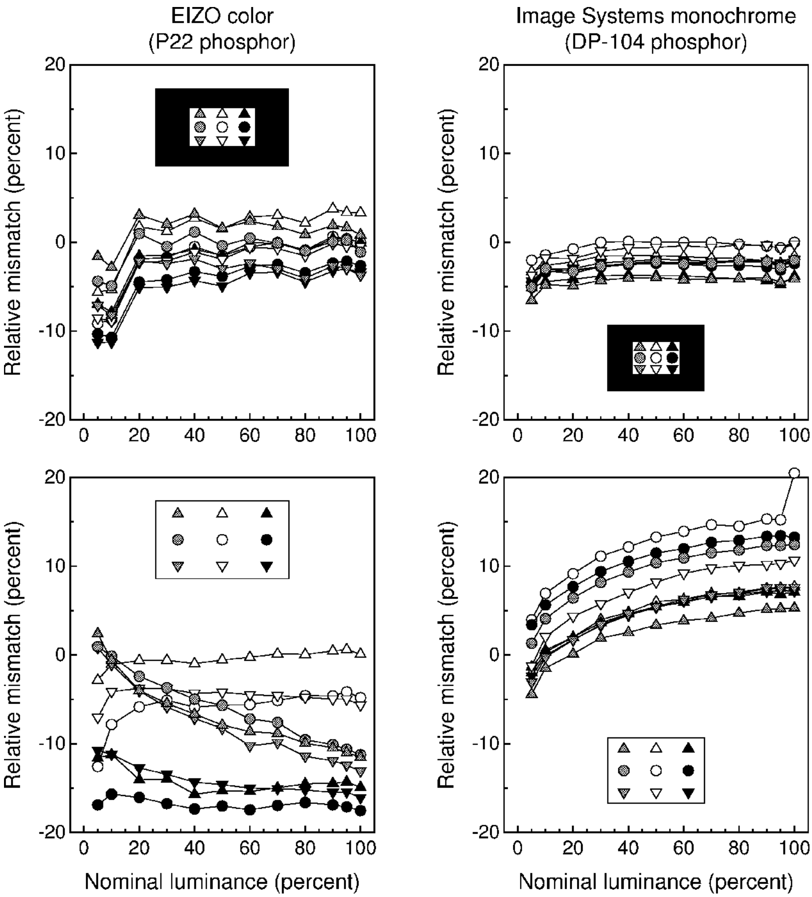

Figure 5. Relationship between actual and nominal luminance at different locations on the monitor (symbols used for data at each location are indicated in the insets, which are drawn to scale of the image area on each CRT). Each symbol represents the average of six measurements. Relative luminance mismatch is defined as 100×(actual-nominal)/nominal. Thus, a horizontal line at an ordinate of 0 indicates perfect match between actual and nominal luminance, as is expected from proper gamma correction. A horizontal line at some vertical offset indicates a fixed percent difference between actual and nominal luminance, something that does not affect linearity. Non-horizontal lines indicate that the relative difference between actual and nominal luminance varies with nominal luminance, something which further indicates that the display cannot be regarded as calibrated at the corresponding location. In the top panels, measurements were taken using a small test field of the same size as that used during calibration; in the bottom panels, the test field covered the entire image area.

4. DISCUSSION

On a calibrated color CRT with P22 phosphor, and also on a calibrated monochrome CRT with DP-104 phosphor, static gratings that nominally differ only as to orientation turn out to differ greatly as to mean luminance and, probably, contrast. The same is true for counter-phase flickering gratings. In the latter case, high-frequency flicker results in a spurious static pattern on the screen, whose contrast is sufficiently high to be detected even though the nominal stimulus cannot be perceived. We believe that Kelly's (1966, 1981) frequency-doubling illusion is only an expression of this artifact of phosphor persistence, which is quite large on a P22-phosphor display.

On another count, spatial variations in luminance across the monitor are generally large, but they are proportional to nominal luminance (and, thus, do not affect contrast) if the monitor has been calibrated using patches of the same size as the background area to be used during the experiments.

Besides Kelly's (1981) case, it appears that some of the artifacts we have described have affected a number of results in the literature, and some of them are discussed next.

4.1. Artifacts in psychophysical measurements of sensitivity to static vertical patterns

Many studies have used gratings with spatial periods and contrast levels within the range where artifactual effects of orientation on sensitivity to static gratings (Fig. 2) will occur. For instance, Polat and Sagi (1994) studied the facilitation caused by flanking gratings of high contrast on the detection of a target grating, using horizontal and vertical gratings with periods of 4 pixels. Woods *et al.* (2000) replicated this experiment using two different viewing distances such that the same retinal sizes and frequencies were obtained either with 4-pixels/cycle gratings (viewed up close) or with 23-pixels/cycle gratings (viewed from an appropriately farther distance). They found that the pattern of results obtained with artifact-prone 4-pixels/cycle gratings (which was similar to that of Polat and Sagi, 1994) was not observed with artifact-free 23-pixels/cycle gratings. Woods *et al.* (2000) also conducted the experiments using the two postural conditions of our psychophysical experiments (upright and lying down), and they found that the results of Polat and Sagi (1994) were affected by the orientation of the gratings with respect to raster lines.

Interactions along raster lines can also explain other results obtained with vertical gratings. Peli (2001) reported that contrast sensitivity for high retinal spatial frequencies was higher when measured at a short observation distance (which implies few pixels per cycle) than when measured from a farther distance (with gratings that had more pixels per cycle). This difference can be explained by the luminance artifacts that we have reported here.

4.2. Artifacts with time-varying patterns: Stereo and image fusion applications

A common trick for the rendition of multi-component patterns is to display their individual components on consecutive frames, using a high frame rate so that the alternation is not perceived. This trick is commonly used to produce plaids (sums of drifting gratings of, at least, different orientations), but there are a number of other applications for image fusion with sequential displays.

Lauritzen *et al.* (1998, 1999) used this technique to combine masking images with target Gabor patches, and they measured detection thresholds for the target as a function of characteristics of the masks and of the relative location of the target within the mask. Without denying an undoubted effect that the mask must have *in ideal conditions*, phosphor persistence must have played a role in their results given the frame rate of 100 Hz (i.e. a frame duration of 10 ms, which is insufficient for phosphor decay). Specifically, Lauritzen *et al.* (1999) reported more masking when the target is on a bright non-textured part of a complex image than there is when this non-textured part is dark. Clearly, residual luminance from a bright area will substantially reduce the actual contrast of a subsequent Gabor patch whose nominal contrast is near threshold, while the negligible residue from a darker area will have a substantially lower effect.

CRT-based frame-sequential-stereo using synchronized shutters suffers 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 (since different phosphors have different decay times) and on its position (since there is more cross-talk at the bottom than at the top of the monitor; Yeh and Silverstein, 1990). Frame-sequential-stereo has been used in image comparison experiments (presenting one image to each eye; Peli and Lang, 2001), where residual luminance may significantly affect the displayed image: this cross-talk can reach 8.5% on our color monitor.

4.3. Artifacts in physiological studies

Psychophysicists can easily conform to experimenting with horizontal gratings if this is the only orientation that is advisable, but neurophysiologists recording from single cells have no choice but to present stimuli at the optimal orientation for the cell, which is rarely horizontal. Oblique stimuli are not well rendered on horizontal raster displays — something that represents another source of stimulus-dependent differences between nominal and actual stimuli (Lages, 1998). Stimuli used in these studies (e.g. Carandini *et al.*, 1997; Walker *et al.*, 1999) are particularly subject to display artifacts, since they involve frame-sequential presentation of sharp-edged patches of drifting gratings of different orientations at relatively high contrasts (30–50%).

One other problem is likely to arise in reverse-correlation studies using white noise (see García-Pérez, 1999), where the stimulus consists of a sequence of bright and dark spots or oriented bars of relatively high contrast (about ±60% of the mean luminance) each of which is displayed for a very short time (usually 20–50 ms). With such short presentation times, phosphor persistence may introduce asymmetries that result in a longer duration (and temporal overlap) of bright spots as compared to dark spots.

5. CONCLUSION

The magnitude of the artifacts we have investigated suggests that a display with a high refresh rate, no horizontal interactions and no persistence beyond the nominal frame duration will be very useful in experiments in which time-varying stimuli, stereo or image fusion are needed. A digital interface (Steemers *et al.*, 2000) may represent a first step towards this goal, since it sharpens the rise and fall of the video signal thus reducing interactions along raster lines. Some non-CRT technologies are also developing which may provide alternative solutions, particularly persistence-free digital micromirror devices. We are currently investigating with one of these displays to find out whether their own specific limitations (Mikoshiba, 2000) have any ramification for vision research.

Until artifact-free displays become fully operational, an accurate model of CRT performance will help to establish the operational range within which a given CRT could be considered dependable. Manufacturers' specifications would also be useful for assessing the suitability of a CRT (or any other display technology, for that matter) for vision research. The set of measurements illustrated in Figs 1, 3 and 5 define a protocol that may provide useful information on the dependability of the display at hand. And the results of its periodical application may prove useful for assessing aging.

NOTES

1. We used these two monitors for their immediate availability. Analysis of other monitors will probably yield similar results.

2. Our estimates of threshold are thus based on a total of 36 reversals, and their precision can be determined from the results in García-Pérez (2000; his Fig. 4) given a reasonable estimate of the spread of the psychometric function. A plausible range for this spread is 0.7–1.0 log units (García-Pérez, 2000; his Fig. 8), which gives standard errors in the range 0.03–0.07 log units for each of our thresholds.

Acknowledgements

Eli Peli was supported by National Institute of Health grants EY05957 and EY12890 and by NASA contract NCC-2-1039. Miguel A. García-Pérez was a Research to Prevent Blindness International Research Scholar, also supported by Dirección General de Enseñanza Superior grant PB96-0597 and by a Career Enhancement grant to Eli Peli from The Schepens Eye Research Institute. We thank Alex Nugent for technical assistance.

REFERENCES

Artal, P., Derrington, A. M. and Colombo, E. (1995). Refraction, aliasing, and the absence of motion reversals in peripheral vision, *Vision Research* **35**, 939–947.

Bach, M., Meigen, T. and Strasburger, H. (1997). Raster-scan cathode-ray tubes for vision research — limits of resolution in space, time and intensity, and some solutions, *Spatial Vision* **10**, 403–414.

Carandini, M., Heeger, D. J. and Movshon, J. A. (1997). Linearity and normalization in simple cells of the macaque primary visual cortex, *J. Neurosci.* **17**, 8621–8644.

Di Lollo, V., Bischof, W. F., Walther-Müller, P. U. *et al*. (1994). Phosphor persistence in oscilloscopic displays: Its luminance and visibility, *Vision Research* **34**, 1619–1620.

Di Lollo, V., Seiffert, A. E., Burchett, G. *et al*. (1997). Phosphor persistence of oscilloscopic displays: A comparison of four phosphors, *Spatial Vision* **10**, 353–360.

García-Pérez, M. A. (1998). Forced-choice staircases with fixed step sizes: asymptotic and small-sample properties, *Vision Research* **38**, 1861–1881.

García-Pérez, M. A. (1999). Direction selectivity and spatiotemporal separability in simple cortical cells, *J. Computational Neurosci.* **7**, 173–189.

García-Pérez, M. A. (2000). Optimal setups for forced-choice staircases with fixed step sizes, *Spatial Vision* **13**, 431–448.

García-Pérez, M. A. and Peli, E. (2000). Saccades, saccadic suppression and the detection of high-temporal-frequency gratings, *Investigative Ophthalmology and Visual Science, Suppl*. **41**, S45.

Groner, R., Groner, M. T., Müller P. *et al*. (1993). On the confounding effects of phosphor persistence in oscilloscopic displays, *Vision Research* **33**, 913–917.

Irwin, D. E. (1994). On the measurement of phosphor persistence in oscilloscopic displays, *Vision Research* **34**, 1623.

Kelly, D. H. (1966). Frequency doubling in visual responses, *J. Opt. Soc. Amer.* **56**, 1628–1633.

Kelly, D. H. (1981). Nonlinear visual responses to flickering sinusoidal gratings, *J. Opt. Soc. Amer.* **71**, 1051–1055.

Klein, S. A., Hu, Q. J. and Carney, T. (1996). The adjacent pixel nonlinearity: Problems and solutions, *Vision Research* **36**, 3167–3181.

Lages, M. (1998). Discrete Fourier analyses of oriented stimulus displays, *J. Math. Psychol.* **42**, 514–515.

Lauritzen, J. S., Hood, S. M., Tolhurst, D. J. *et al*. (1998). Detection of Gabor patches embedded in natural images, *Perception, Suppl*. **27**, 151.

Lauritzen, J. S., Pelah, A. and Tolhurst, D. J. (1999). Perceptual rules for watermarking images: A psychophysical study of the visual basis for digital pattern encryption, *SPIE Proceedings* **3644**, 392–402.

Metha, A. B., Vingrys, A. J. and Badcock, D. R. (1993). Calibration of a color monitor for visual psychophysics, *Behavior Research Methods, Instruments and Computers* **25**, 371–383.

Mikoshiba, S. (2000). Visual artifacts generated in frame-sequential display devices: An overview, *SID 31 Digest* 384–387.

Mulligan, J. B. and Stone, L. S. (1989). Halftoning method for the generation of motion stimuli, *J. Opt. Soc. Amer. A* **6**, 1217–1227.

Peli, E. (1992). Display nonlinearity in digital image processing for visual communication, *Optical Engineering* **3**, 2374–2382.

Peli, E. (2001). Contrast sensitivity function and image discrimination, *J. Opt. Soc. Amer. A* **18**, 283–293.

Peli, E. and Lang, A. (2001). The appearance of images through a multifocal, intraocular lens, *J. Opt. Soc. Amer. A* **18**, 302–309.

Pelli, D. G. (1997). Pixel independence: Measuring spatial interactions on a CRT display, *Spatial Vision* **10**, 443–446.

Polat, U. and Sagi, D. (1994). The architecture of perceptual spatial interactions, *Vision Research* **34**, 73–78.

Sherr, S. (1993). *Electronic Displays*, 2nd edn. Wiley, New York.

Steemers, H., DaCosta, V., Martin, R. *et al*. (2000). Developing a digital interface for the CRT monitor, *SID 31 Digest* 150–153.

Swift, D., Panish, S. and Hippensteel, B. (1997). The use of *VisionWorks*™ in visual psychophysics research, *Spatial Vision* **10**, 471–477.

Walker, G. A., Ohzawa, I. and Freeman, R. D. (1999). Asymmetric suppression outside the classical receptive field of the visual cortex, *J. Neurosci.* **19**, 10536–10553.

Westheimer, G. (1993). Phosphor persistence in oscilloscopic displays, *Vision Research* **33**, 2337–2338.

Westheimer, G. (1994). G. Westheimer responds, *Vision Research* **34**, 1621.

Wolf, W. and Deubel, H. (1997). P31 phosphor persistence at photopic mean luminance level, *Spatial Vision* **10**, 323–333.

Woods, R. L., Nugent, A. K. and Peli, E. (2000). Bandwidth affects visual lateral interactions, *Investigative Ophthalmology and Visual Science, Suppl.* **41**, S803.

Yeh, Y.-Y. and Silverstein, L. D. (1990). Limits of fusion and depth judgement in stereoscopic color displays, *Human Factors* **32**, 45–60.