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Pixel independence: measuring spatial interactions on a CRT display

DENIS G. PELLI*

Department of Psychology, New York University, 6 Washington Place, New York, NY 10003, USA

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Abstract—The standard working assumption of careful CRT imaging is that each pixel is imaged independently, through a point nonlinearity (the monitor's gamma function, relating screen luminance to input voltage), and then blurred by the point-spread function of the beam spot on the phosphor. Unfortunately most monitors have inadequate video bandwidth, DC restoration, and high-voltage regulation to live up to this ideal model. Two tests are recommended for assessing a CRT's deviation from the pixel-independence model.

Using a computer to display an image on a cathode ray tube (CRT) monitor is a two-step process: first digital, then analog. The digital part is perfect (i.e. conforms to a simple model), but the analog part is far from perfect, requiring a rather complicated model for even moderately accurate imaging. Digital-to-analog converters (DACs) are generally accurate to within half a voltage step, but part of that error (the 'glitch') depends on the digital codes of both the current and preceding pixels (Brooktree, 1989). We have previously discussed how to minimize the consequences of these DAC errors (Pelli and Zhang, 1991; also see Tyler, 1997). Here I consider the CRT monitor.

The standard working assumption of CRT imaging is that each pixel is imaged independently, through a point nonlinearity (the monitor's gamma function, relating screen luminance to input voltage), and then blurred by the point-spread function of the beam spot on the phosphor (Banbury, 1982; Infante, 1985). The gamma function is typically well described by a function like $L = L_0 + a(V - V_0)^\gamma$, provided $V \geqslant V_0$, where a, L_0, V_0, and γ are fitted parameters affected by the settings of the contrast and brightness knobs (Keller, 1991); γ is typically around 2.3. The (DC-normalized modulus of the) Fourier transform of the point spread function is the modulation transfer function (MTF), which is easier to measure and take into account than the point-spread function itself (Pelli and Zhang, 1991). Thus the pixels may overlap (because of the blur) but are independent. This CRT model is widely used to

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*denis@psych.nyu.edu; http://rajsky.psych.nyu.edu/VideoToolbox

calibrate and correct for the individual monitor's characteristics, to accurately display stimuli with known luminance profiles. However, the pixel-independence assumption is usually false. The independence assumption is important because it underlies all attempts to linearize CRTs by gamma correction. Trying to correct for a nonlinearity that involves multiple pixels would be difficult. However, one can avoid these effects by buying a monitor that minimizes them, or by careful stimulus design (see Pelli and Zhang, 1991). The rest of this note discusses the three main reasons for failure of pixel independence, and describes two practical tests to assess the degree of failure.

To assess a monitor's pixel-independence: (1) compare the mean luminance of a fine 100%-contrast grating (alternating white and black pixels) oriented vertically (which stresses the video bandwidth) vs. horizontally (which doesn't); (2) measure the percent luminance change of a 4-cm-wide vertical gray strip in the middle of the screen when the rest of the screen changes from white to black.

There are three reasons for failure of the independence assumption: insufficient video bandwith, imperfect DC restoration, and inadequate high-voltage regulation. Some manufacturers seem to be interested in making research-grade video monitors that would have independent pixels, i.e. high video bandwidth, DC coupling (instead of DC restoration), and good high-voltage regulation.

Insufficient video bandwidth has the effect of low-pass filtering the incoming video signal. At first it might seem that this would be equivalent to optically blurring the image horizontally, i.e. merely extending the monitor's point spread function. That would be true if the limited video bandwidth low-pass filtered the beam current (to which screen luminance is proportional), but instead it low-pass filters the drive voltage. Luminance is proportional to current, not voltage. Thus the voltage averaging occurs before the nonlinear gamma function, whereas current (or luminance) averaging would occur afterwards, like optical blur, which doesn't affect the mean luminance. Alternating black and white pixels are a critical test. Comparing the mean luminance of fine vertical and horizontal gratings is a good way to measure this effect, as many authors have noted previously (see Lyons and Farrell, 1989; Naiman and Makous, 1992; Hu and Klein, 1994).

Inadequate high-voltage regulation is another common cause for failure of pixel independence. Setting a large fraction of the screen to maximum luminance (i.e. white) may pull enough beam current to run down the high voltage (typically 15 kV). The high voltage may take several milliseconds to recover from this 'droop', and the beam will be dimmer until the voltage recovers. The high voltage will usually recover during the 1 ms or so blanking (i.e. zero current) interval between frames, so this effect will be minimal at the top of the display (drawn first) and maximal at the bottom (drawn last).

Unfortunately most video displays are not DC coupled. Instead they are AC coupled for most of the time, and momentarily DC coupled to make zero volts produce black at the end of the synch interval. This is called 'DC restoration', which is slightly cheaper to design and build than a fully DC-coupled video circuit. If the AC time constant were much longer than a frame, the DC restoration would be equivalent to DC coupling, but in practice the AC time constant is typically short relative to the length of the frame, so that the same input voltage will produce different screen luminances depending on what the average voltage has been since the last blanking interval.

Both of these effects will depend on an average (current or voltage) since the last blanking. After a big white patch, high voltage droop will make the bottom of the screen dimmer, while the AC coupling of DC restoration will make it brighter. I suspect that the manufacturers of color monitors take more trouble to minimize these effects because hue errors are more obvious than luminance errors.

One can measure the combined effect of both defects by measuring the luminance of a vertical gray strip (e.g. 4 cm wide) running down the middle of the display while alternately displaying white and black on the rest of the screen. We suggest 4 cm width because the strip should be much bigger than the point spread, yet still occupy only a small fraction of the screen area. On a color CRT the two effects may be distinguished by virtue of the fact that the DC restoration is independent between guns, but the high voltage is shared by all three guns.

Luminance measurements are usually done with a photometer, but it would be useful to create software that accurately measured these pixel-independence failures by allowing the observer to null the luminance errors visually, without any equipment beyond the computer and display. For example, one might alternate the two conditions at 4 Hz, producing flicker, and allow the observer to control a luminance offset that is applied to one of the two conditions, to null the flicker. Care must be taken not to involve visual nonlinearities. When looking at the fine grating alternating between vertical and horizontal the observer should stand far enough away to be unable to resolve the gratings. When judging the artifactual flicker of the nominally steady gray strip in the middle of a white-black flickering field, the observer should occlude most of the display, exposing only part of the gray strip.

If these worst-case tests reveal unacceptably large luminance errors, it may be possible to minimize the error in the rendering of actual experimental stimuli by careful stimulus design, avoiding very high and very low spatial frequencies. Avoid high frequencies: doubling the observer's viewing distance will halve the video bandwidth needed to produce the same visual stimulus. Avoid low frequencies: in order to eliminate DC effects, it may be possible to add an obscured flank at the side of the screen that compensates for changes in mean luminance of the visible part of the screen.

CONCLUSION

These measurements document CRT characteristics that affect stimulus luminances yet are difficult to model and correct for. I recommend the measurements because any claim to have specified visual stimuli depends on either directly measuring the stimulus produced (which is usually impractical) or on having a CRT model that accurately predicts the image. Accounting for the monitor's gamma and MTF (or blur) is about as far as most of us are willing to go in image synthesis, which is enough if pixel independence holds. By measuring the degree to which this model fails, we can (1) specify upper bounds on the errors of our stimulus specification; (2) choose monitors and stimuli that minimize the error; and (3) encourage manufacturers to produce monitors better suited to accurate image display.

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