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Raster-scan cathode-ray tubes for vision research—limits of resolution in space, time and intensity, and some solutions

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Abstract—Raster based cathode ray tubes (CRTs) are increasingly used for stimulus presentation. While very flexible their design based on consumer electronics can limit their value in vision research. Here their limitations of resolution in time space intensity and wavelength are systematically compiled. Often, ingenious ideas can circumvent such limitations for specific experiments Some *ad hoc* solutions, as well as the more general techniques of dithering and anti aliasing are presented

1. INTRODUCTION

Computer-controlled visual display units are increasingly used to present stimuli for vision experiments. With few exceptions, they are designed for consumer electronics, are developed under commercial constraints for large quantity production, and represent a compromise between image quality and cost within current technology. Vision science therefore, through its interest in the limits of vision, immediately encounters the limitations of the apparatus

Most vision experiments now use raster-based cathode-ray tubes (CRTs) Usually, they are based on raster-scan techniques which are, in many respects, excellently suited for visual stimulus presentation (Watson *et al*, 1986) Programming for stimulus generation is a typical case of 're-inventing the wheel' Many of the problems and their solutions presented in this paper have occurred to other authors (for summaries see Cowan, 1983, 1995, Mollon and Baker, 1995, Brainard, 1996) A wide dissemination of awareness of methodological problems seems useful Instead of an in-depth treatment, we present here a systematic overview of all the problems that have occurred to us, or we have found in the literature or identified in discussions

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Table 1.

CRT artifact classification scheme Artefacts are arranged on the dimensions of space, time, and intensity, and interactions thereof On the diagonal are artifacts confined to just one of these dimensions; e.g. the orientation of a line can affect its width, which is a purely spatial artifact. Off-diagonal are interactions between dimensions e g presenting a stimulus at different screen locations affects its time of appearance relative to the start of the frame, an artifact that mixes space and time; horizontal lines will generally have a higher intensity than vertical ones an artifact that mixes space and intensity. In some cases numbers are given that hint at the size of the artifact

Interactions between	Space	Time	Intensity (colour)
Space	• upper limit to spatial frequency • staircase artifacts • line orientation-width artifact	• stroboscopic artifacts with moving periodic patterns • interaction of time and screen location [10 ms]	• orientation-dependent intensity [50% error] • screen inhomogeneity [up to 30% error] • large and bright stimuli overload power supply • bright stimuli become blurred
Time		• temporal resolution limited by frame rate	• phosphor decay time [μs–ms] • phosphor ageing [months]
Intensity (colour)			• limited max. intensity • non-linearity ('gamma') • limited video-DAC resolution • limited colour gamut • colour gun interaction

with colleagues. Furthermore, we offer some possible solutions. Three areas will be covered: (1) limits of resolution in space, (2) limits of resolution in time, and (3) limits of resolution in intensity and colour and limited colour gamut. To bring some order into the discussion, a systematic classification scheme of CRT artifacts is shown in Table 1, which also notes some of the stimulus artifacts that can result from a combination of limitations in each of these areas.

2. LIMITS OF RESOLUTION IN SPACE

2.1. Requirements for a visual stimulus

What level of spatial resolution is required? Let us assume that we want to explore the human contrast sensitivity function and need to generate appropriate sinewave-grating stimuli on a CRT. The highest spatial frequency resolvable by human beings is about 30 $\mathrm{cyc\,deg^{-1}}$. From Nyquist's sampling theorem, one cycle of a horizontal or vertical grating, having the maximum spatial frequency f_{max} that can be realised on a CRT, has a period of 2 pixels (it will not be sinusoidal). The required pixel size x_{p} to achieve a specific f_{max} is thus given by

$$x_{\mathrm{p}} = \frac{\pi d}{360^{\circ} f_{\mathrm{max}}}, \tag{1}$$

where d denotes the observer distance. At a typical reading distance of 40 cm for example, the required pixel size for a grating to be at the resolution limit of a young observer would be 0.12 mm. This is below the typical pixel size, or 'dot pitch', of current colour monitors which is around 0.25 mm (corresponding to 100 dpi). Thus, to reach the highest spatial frequency, the observer distance must be increased; based on the above, at least 80 cm is needed for a young observer, unless a monitor with smaller pixel size is available.

The spatial sampling rate from pixel quantisation limits not only the highest obtainable spatial frequency but also the increment between spatial frequencies that can be realised: to prevent spatial aliasing, spatial frequencies must not only be below the Nyquist frequency limit but must also be at integer divisors of the latter (Strasburger and Rentschler, 1986; see there for efficient methods of grating generation). The next lower spatial frequencies that are realisable thus have 4, 6, ... pixels per cycle. To extend the example above: with a dot pitch of 0.25 mm and observer distance at 80 cm, realisable spatial frequencies are thus 30, 15, 10, ... $\mathrm{cyc\,deg^{-1}}$. Further limitations in spatial resolution arise from interactions with intensity and time; they will be discussed below.

2.2. *Electron optics*

The spatial resolution of CRTs is limited by electron optics. The spot on the screen is an image of the cathode. A smaller spot size is equivalent to a smaller active area of the cathode; it is only possible with decreased maximum luminance, as high electron density leads to widening of the beam through space-charge effects. With colour devices, additional constraints arise through the presence of the shadow mask, or the stripes in the case of the Trinitron tube. Consequently, it seems unlikely that large size CRTs with pixel sizes below 0.1 mm and sufficiently high luminance will become available in the near future.

Electron optics are also responsible for changes in the pixel point-spread function with different levels of intensity (Lyons and Farrell, 1989; Naiman and Makous, 1992). Simply stated, increasing the brightness often blurs the stimulus.

2.3. *Staircases, jaggies and width artifacts*

Two kinds of spatial artifacts result from the 'pixelation' of the image. (1) Straight lines on a raster-scan device are normally drawn using a digital differential analyser algorithm (Bresenham, 1965; Horn, 1976; Newman and Sproull, 1979). This leads to 'staircase' effects or 'jaggies' which are particularly visible in lines that differ only slightly in their orientation from horizontal or vertical. (2) Line thickness varies with orientation: depending on the exact shape (circular vs. square) of the virtual pen used to draw the lines, lines at 45 deg can be markedly wider than horizontal or vertical lines.

2.4. Some methods of increasing spatial resolution

2.4.1. Trading stimulus size vs. spatial resolution What can be done about the limited spatial resolution of CRTs? If fine detail is required one can, of course, simply increase the observer distance to 3 m or more (see Eqn (1)) In turn, the maximum stimulus size will decrease, however The compromise between spatial resolution and field size may be unacceptable in a number of research situations For the measurement of visual acuity, it turns out that even at 5 m observer distance, anti-aliasing (explained below) is required to achieve sufficient resolution for measuring high acuities (Bach, 1996, 1997b).

2.4.2. Tricks. Sometimes, stimuli can be found that distribute staircase artifacts evenly between stimulus conditions such that they cannot be used as a discriminative cue Meigen *et al* (1994), for example, wanted to assess perceptual interactions between oblique lines The tested line orientations were 0 deg and 16 deg. By tilting the CRT by 8 deg, the orientations were transformed to be −8 deg and +8 deg. Consequently, both line orientations suffered from identical staircase effects so that any experimentally found differences must have been visual.

2 4 3 Anti-aliasing A powerful method to increase spatial resolution is called 'anti-aliasing' Anti-aliasing increases spatial resolution through luminance modulation. The term is derived from Nyquist's sampling theorem (see earlier): if the spatial or temporal signal to be sampled contains energy at frequencies higher than twice the sampling frequency, these high frequencies are 'folded' downwards into the displayed spectrum and appear as 'alien' frequencies. Aliasing occurs in computer graphics because the pixel raster undersamples many graphical shapes and thus introduces such additional, alien frequencies.

Anti-aliasing is well known in computer graphics (Foley *et al.*, 1983, 1990) and can best be explained graphically (see Bach, 1997b): the representation of an arbitrary graphical shape by an array of pixels can be imagined as the squares on graph paper, partially covered by the shape. Without anti-aliasing, a pixel in a black and white picture is black if covered by more than half by the graphical shape and is white otherwise With anti-aliasing, pixel size remains the same but luminance is used to carry additional spatial information: instead of being black or white, a pixel's intensity is set proportional to the pixel's area covered by the desired shape. Similar interpolation can be used for coloured pictures After low-pass filtering through the optics of the eye, the retinal image of an anti-aliased image approximates the same image rendered with a smaller pixel size (depending on observer distance) Anti-aliasing improves the readability of small type at the cost of a slight blur and there now exist hardware methods for rapidly displaying anti-aliased text. Anti-aliasing is available in many software packages (e.g. Photoshop) and is also a built-in feature of the Apple Macintosh operating system. We have used it to improve psychophysical stimuli (Meigen *et al.*, 1994) and in the 'Freiburg Visual Acuity Test' (Bach, 1996, 1997b).

3. LIMITS OF RESOLUTION IN TIME

3.1. Frame rate stroboscopic effects

An obvious limitation on the display of moving or flickering stimuli on a CRT is introduced by the temporal sampling imposed by the frame rate. Frame rate not only determines the highest frequency of change, but also temporal sampling: only stimulus updates at integer multiples of the frame interval can be used; otherwise temporal aliasing will occur, presenting as stroboscopic (wagon-wheel) effects or beats. This limits the choice of temporal stimulation frequencies, particularly at the higher frequency end. Note that the concept of a 'frame' as an event in time, which is implicitly used in explaining temporal aliasing, is a simplification: a frame is not presented instantaneously but is scanned (see, for instance, Bach, 1997a, for temporal envelopes), and the percept of a field is the result of temporal integration both through phosphor persistence and visual persistence.

3.2. Phosphor and time

Phosphor decay, which happens over the microsecond and millisecond range but can last up to seconds, plays an important role whenever precise control of timing is required and has often not received adequate attention. One consequence of decay is that the contrast of moving stimuli is lower than that of stationary stimuli, the extent of the reduction being difficult to measure. Many phosphors have complex decay functions, consisting of a primary rapid decay followed by a prolonged afterglow (Cowan and Rowell, 1986; Mollon and Baker, 1995). Mollon and Baker (1995) describe major scientific errors that resulted from these effects.

The visibility of stimuli in short-exposure experiments is affected by a complex interaction of physical and perceptual factors that make it difficult to predict visibility in a given situation. Di Lollo *et al.* (1997) analyse the condition of bright stimuli on a dark background and demonstrate the necessity of perceptual control experiments to avoid artifacts. Wolf and Deubel (1997) study the persistence of stimuli on scotopic and photopic backgrounds, with refreshed displays, and show a sluggish offset stemming from phosphor characteristics that may be unrelated to the commonly considered phosphor decay functions.

Phosphor ageing is a further area of concern. Although the general intensity loss from ageing is easily corrected for by recalibration, the experimental design might be jeopardised because a required luminance level that was available at the beginning of a long experiment may be out of range after some months of experimentation.

3.3 Motion of periodic stimuli: spatio-temporal aliasing

Periodic stimuli are subject to artifact-generating interactions of spatial and temporal frequencies. This sets an upper limit for the product of spatial frequency (for periodic stimuli) and speed to avoid the wagon-wheel effect. For an artifact-free display of periodic moving square-wave gratings, there is a simple relationship between maximum speed $v_{\max}$ [deg s^{-1}], maximum spatial frequency $f_{\max}$ [cyc deg^{-1}] and frame rate (monitor frequency), f_{frame} [Hz]:

$$v_{\max} \times f_{\max} = f_{\text{frame}}/4. \qquad (2)$$

The denominator has a value of 4 for the following reasons. For unique identification of direction, the maximum shift must be less than 1/2 of a period. Since the minimum shift is one pixel (to avoid further artifacts from non-integer pixel shifts), a moving grating with a 2-pixel period cannot be realised, the highest spatial frequency thus having a period of 4 pixels (this holds for square-wave gratings; for sinusoidal gratings 3 pixels would suffice). For lower spatial frequencies, the maximum shift is between 1/4 and 1/2 of a period; thus Eqn (2) is based on the 'worst case', i.e. it gives the lowest upper limit for the product that holds for all spatial frequencies. Note that Eqn (2) does not depend on observer distance. Speed is thus more limited for high than for low spatial frequencies.

Incidentally, reprogramming of a graphics board's timing parameters will be restricted by a trade-off between spatial and temporal resolution if the pixel clock stays constant. A constant pixel clock unfortunately prohibits pushing up the limit given by Eqn (2) by increasing the frame rate.

3.4 Interaction of time and screen location

When timing accuracy in the millisecond region is required, it is important to remember that pixels lower in the display are drawn later, it takes, for example, about 15 ms to paint a frame on a 67-Hz display. Fortunately, once this is recognised, correction factors can easily be applied, at least for small objects ('correction for scan delay'; Sutter and Tran, 1992).

4. LIMITS OF RESOLUTION IN INTENSITY AND COLOUR

4.1 Gamma

The relationship between video voltage and luminance output of the screen is nonlinear (Foley and Van Dam, 1983; Poynton, 1993, 1996). At the low-luminance end, there is a floor effect that depends on the luminance and contrast controls of the CRT. In the medium luminance range, luminance can well be described by a power function $L \approx v^{\gamma}$, where γ is a positive constant, with a value typically between 2 and 3. The effect is due to the grid-controlled valve characteristic (Grivet, 1965) but often erroneously attributed to 'phosphor non-linearity'. For example, Foley and

Van Dam (1983, p 594) state that the light output by a phosphor is related to the number of electrons by a power function with exponent γ. This statement is in contradiction with established physical knowledge. Ardenne (1973, p. 170), Cowan (1995), Forand *et al.* (1990), and others state a linear relationship between beam current and the number of emitted photons.

In addition to the fairly well-known gamma-non-linearity, saturation effects occur at high intensities due to current limitations of the high-tension power supply that feeds the tube The effect is more pronounced for large bright areas than for small ones. These beam-current limitations vary widely between different brands of CRTs. In most cases they also depend on the spatial extent of the stimulus since beam current can often be sustained for small but not for large stimuli. If the desired intensity range can be limited to the parabolic part of the function, the non-linearity can be overcome by gamma correction, which derives its name from the symbol used for the exponent (which, in turn, stems from the field of photography, where it is used to describe the transfer characteristics of photographic material). Gamma correction can be done in various ways (e.g. Stanislaw and Olzak, 1990; Pelli and Zhang, 1991; Metha *et al* , 1993, Poynton, 1993); some CRTs have it already built in.

4 2 Horizontal lines are brighter than vertical lines

As can be easily verified, in all raster-scan CRTs a one-pixel horizontal line is brighter than a vertical one (Pelli, 1997). The reason for this effect is the limited video signal bandwidth that attenuates the rapid horizontal signal variation required to render a vertical thin line but not the slower vertical variation across raster lines followed by CRT non-linearity.

The luminance difference is quite strong and can introduce serious luminance artifacts in vision experimentation. The error increases with decreasing pixel size at constant dot pitch and can exceed 50%. Sometimes, it can be overcome by a trick: in an experiment that used texture patterns composed of oriented line segments, we needed horizontal (0 deg) and vertical (90 deg) lines without introducing luminance artifacts. We tilted the CRT by 45 deg and drew the lines at ±45 deg. This removed the luminance differences while still presenting the stimuli at 0 deg and 90 deg as desired (Bach and Meigen, 1992; Solomon *et al.*, 1993; for a different solution see Solomon and Sperling, 1995).

4.2.1. Software solution: bandpass-filtered noise textures. For independent control of orientation and spatial frequency, Gabor-filtered noise textures (Landy and Bergen, 1991) or some generalization thereof might be considered. Low-pass filtering introduces a correlation between neighbouring pixels, which reduces aliasing and orientation-intensity artifacts.

4.3. Spatial screen inhomogeneity

Most CRTs have marked luminance inhomogeneities across the screen (see, e.g. Cook *et al.*, 1993). Metha *et al.* (1993) measured a more than 20% drop in the periphery vs. the centre of a high-quality CRT. Bohnsack *et al.* (1997) carefully measured relevant properties of the Sony 17se display and found a 13% drop of luminance in the periphery. This problem can easily be overlooked, as the low-spatial-frequency attenuation of the human contrast sensitivity function renders this effect unnoticeable at normal observer distances.

4.4. Bit depth of video DACs

To produce the video voltage, digital-to-analogue converters (DACs) of 8-bit resolution per colour gun are used in most current commercial computer graphics. The resulting 256 different intensity levels are insufficient for assessment of the human contrast threshold. For an evenly-spaced scale of 256 intensity levels starting from black, the contrast resolution would be 1/128 near half maximum luminance. However, the monitor's accelerating gamma characteristic approximately doubles the step size in that region, so that the smallest contrast is about 2% in Michelson units. The VGA standard specifies a still lower luminance resolution of (3×) 6 bits.

4.5. Limited colour gamut

With 8-bit DACs, 256 different intensity levels can be produced for each gun: red, green and blue. This yields $256 \times 256 \times 256 \approx 17$ million different colours. Because phosphors are spectrally broadband, the saturation of the available colours is limited (Foley and Van Dam, 1983; Brettel, 1988), which restricts colour-vision experiments. Finally, the spectral radiant power distribution of the available colours restricts the application of computer monitors in colour-matching experiments. It is, for example, not directly possible to simulate a Nagel anomaloscope on a colour monitor, since three independent light sources, red, green and yellow, are required that lie on the colour confusion lines for dichromates. While three monitor colours can easily be found that lie either on confusion lines for protanopes or on those for deuteranopes, they cannot be independent, as yellow always consists of a colour mixture of red and green It is also not possible to replicate the fundamental colour matching experiment on a CRT, as any perceptual match between two CRT patches will be a physical match

The three R-, G-, and B-guns can interact in various ways, including crosstalk in the graphics board, wiring and video amplifiers, and misalignment of the shadow mask. The reader is referred to Cowan and Rowell (1986), Brainard (1989), and Mollon and Baker (1995) for a detailed discussion of these intricate problems.

4 5 1 Hardware solution 1: reduced monitor contrast range. For many experiments it may be sufficient to cover only a small range of the contrast and use the full 1/256 resolution in this range This has been done in various ways

- optically mixing a homogenous field with a monitor (e g Poirson and Wandell, 1996),
- optically mixing two monitors (Foley and Boynton, 1993),

- adjusting the manual controls of luminance and contrast on the CRT such that the 256 intensity levels are mapped into the desired range (e.g. Cole *et al.*, 1993).

4.5.2. Hardware solution 2: use of a $\geqslant$ 12 bit DAC. The use of a $\geqslant$ 12-bit DAC is the preferred solution when high intensity or colour resolution or both is desired, provided the DAC is sufficiently fast. The combination of high spatial resolution (high number of scan lines) and high frame rate requires settling times that are near the edge of current technology.

If only one-dimensional stimuli are required, one can modulate the stimulus in the 'slow' direction of the beam only (at line frequency rather than at pixel frequency). This was done, for instance, in some versions of the VSG graphics system from Cambridge Research Systems. When vertical gratings are required, the CRT can be turned on its side (colour artifacts may arise if the shadow mask is consequently dislocated; this may be remedied by degaussing).

4.5.3. Hardware solution 3: cascading DACs. DACs often have a high linearity compared with step size. Thus it makes sense to 'cascade' DACs: the output of one DAC is added to the scaled output of a second. The three DACs of a colour board can be combined with a few resistors to produce a high-resolution monochrome signal, or two colour boards can be combined to produce a high-resolution colour signal. This technique was discovered independently by a number of authors and is described, with full calibration details, by Pelli and Zhang (1991).

4.5.4. Hardware solution 4: attenuation of the video signal. Attenuation of the video signal by a passive resistor network with computer-controlled relays provides the highest possible resolution at low contrast. This is fairly simple to realise with modern raster-scan CRTs that have separate inputs for video and synchronisation signals and with X-Y-Z displays (also called vector or point-plotting displays), as for example with Finley's (1997) device. Denis Pelli produced some prototype boards in the early eighties. Attenuation by a factor of 128, for example, with an 8-bit DAC results in a contrast resolution equivalent to $8 + 7 = 15$ bits. The highest attenuation is limited by video-signal cross talk on the attenuator. With older, composite-video raster-scan CRTs, the accessory signals (sync and porch) need to be treated separately which requires additional circuitry (Strasburger, 1996).

4.5.5. Software solution 1: dithering. If high spatial resolution is not required, luminance or colour resolution or both can be improved at the cost of spatial resolution by 'dithering' (Foley and Van Dam, 1983; Savoy, 1986; Ulichney, 1987; Mulligan and Stone, 1989). Dithering can be viewed as the opposite of anti-aliasing. There are three types of dithering: error diffusion, ordered dithering, and random dithering. In dithering by error diffusion, a luminance error is defined for each pixel,

$$\textit{Error} = \textit{requested intensity} - \textit{closest available intensity},$$

where the requested intensity is the luminance of the current pixel plus a certain part of the error term of the surrounding pixels. Ideally, the error term is spread evenly among all surrounding pixels. In the Apple Macintosh operating system, the built-in dithering algorithm pushes half the error to the left or right, and the other half to the pixel immediately below (Othmer and Lipton, 1992). Dithering by error diffusion is used in the contrast threshold section of the 'Freiburg Visual Acuity Test' (Bach, 1996, 1997a) where sub-threshold contrasts are thus easily achieved.

4.5.6. Software solution 2: 'bit stealing'. Tyler recently described an ingenious variation of dithering, which he calls 'bit stealing' (Tyler *et al.*, 1992, Tyler, 1997). Fine variations of luminance are achieved through small changes in hue, the latter kept small enough to stay below the threshold for chromatic detection. By carefully distributing values between the R, G, and B channels, the luminance resolution can be increased by a factor of about 4. In vision experiments, possible artifacts arising from sub-threshold summation and facilitation should be assessed before relying on any of these techniques.

5. CONCLUSION

Computer-controlled CRTs are inexpensive, bright, have high resolution, and are easy to use Advances in computer technology make it easier to design sophisticated stimuli to manipulate perception and study its mechanisms. However, CRTs also have limitations due to quantization in time, space and intensity, possibly giving rise to obvious and sometimes to subtle artifacts. If the inherent limitations are recognised early (Table 1), they can often be avoided by systematic or ad-hoc solutions, depending on the specific type of experiment.

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