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Visual calibration of CRT monitors

Elisa Colombo[a], Andrew Derrington[b,*]

[a]Instituto de Luminotecnia, Avenida de Independencia 1800, 4000 Tucuman, Argentina
[b]School of Psychology, University Park, Nottingham NG7 2RD, UK

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Abstract

In this paper, we develop and test a technique for calibrating a computer-controlled television monitor using a visual comparison instead of a photometer. The basic principle of the calibration is to compare a patch of pixels that are uniformly driven for an adjustable voltage with a patch in which a predetermined fraction of the pixels are set to the maximum voltage and the remainder are set to the minimum. By adjusting the voltage to make the two patches appear equally bright we get an estimate of the voltage that produces the predetermined fraction of the maximum luminance.

Smooth functions were fit to the relationship between the DAC output and the fraction of illuminated pixels using a least-squares method, and used to estimate the function relating screen luminance to voltage. This function was then used to calculate lookup tables for linearisation. Sinusoidal and beat (sum of two sinusoids) luminance modulations were generated from the calibrated lookup tables and their profiles were measured with a photometer in order to check the calibrations.

We find that visual calibration is sufficiently reliable to be used as an alternative to calibration using a photometer. It is easier and cheaper than using a photometer: a good photometer can be more expensive than the combined cost of the computer, graphics card and monitor.

Keywords: Vision; Psychophysics; Display non-linearity; Calibration; CRT monitors

1. Introduction

In recent years, the use of computers with graphics cards for the presentation of patterns of controlled contrast on video monitors has become widespread, owing to the reduction in cost of this type of hardware. One area in which computers have become indispensable is in visual psychophysics. Today, a typical laboratory set up for psychophysics consists of a personal computer, a cathode-ray-tube (CRT) display for stimulus presentation, a set of software applications for data analysis and presentation. However, although the CRT display allows flexible control of the spatial, temporal and chromatic properties of visual stimuli, it has important limitations that must be measured, and compensated if the stimulus delivered to the subject is to be what the experimenter requires.

The non-linear relationship between video voltage and luminance output of the screen is the most important source of errors [1]. It is absolutely essential to correct this non-linearity to avoid artefacts in visual stimuli, which might otherwise give rise to apparently non-linear properties in the visual system. The normal method of correcting the non-linearity is to measure the relationship between screen luminance and video voltage (the gamma function) using a photometer and to incorporate the inverse relationship into the stimulus generating software.

This approach has two drawbacks. First, using a photometer to calibrate a visual display requires a degree of technical expertise. Second, photometers are expensive. Although the degree of expertise required can be minimised by good software and well-written instruction manuals, cost is increasingly a barrier. The increasing consumer use of personal computers and the increasing power of their graphics is driving down the cost of the other components of a computer-based vision laboratory. However, a photometer is still a specialised piece of equipment and its cost is increasing in relation to the cost of the other components of a computer-based vision laboratory. Indeed the basic requirements for many visual tests would be met by the equipment many people use to access the internet, so in principle visual tests could be delivered over the internet. However, a fundamental prerequisite for such an approach would be a method of calibrating a computer-graphics display that could be used by an inexperienced operator

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* Corresponding author. Tel.: +44-115-951-5362; fax: +44-115-951-5324.

E-mail address: andrew.derrington@nottingham.ac.uk (A. Derrington).

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without any specialised equipment. It is the purpose of this paper to evaluate the possibility of developing such a method.

We develop and test a technique for calibrating a computer-controlled television monitor using a visual comparison instead of a photometer. The basic principle of the calibration is to compare a patch of pixels that are uniformly driven with an adjustable voltage with a patch in which a predetermined fraction of total number of pixels are set to the maximum voltage and the remainder are set to the minimum. By adjusting the voltage to make the two patches appear equally bright we get an estimate of the voltage that produces the predetermined fraction of the maximum luminance. By fitting an appropriate smooth function to a set of such estimates we can estimate the shape, but not the absolute level, of the gamma function. We show that this calibration technique allows us to generate simple and complex periodic waveforms that are substantially free of distortion artefacts.

2. Methods and procedure

2.1. Procedure for a photometric calibration

The traditional manner of calibrating a monitor is to use a photometer to measure the relationship between the luminance of a small patch of pixels on the screen, and the applied voltage generated by the DACs controlling the luminance of pixels within that area. By measuring about 10 values it is possible to get enough data to estimate the relationship between both variables: luminance (L) and DAC output (D). If we consider an ideal display, the function relating display luminance and voltage would be linear, in practice, this function is found to be non-linear. 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, actual luminance is typically modelled by a power function:

$$L = D^{\gamma}, \tag{1}$$

where γ is a positive constant with a value typically between two and three that depends, among other things, on the luminance and the contrast settings of the screen and which particular phosphor is being examined. In addition to the well-known gamma-non-linearity, saturation effects can occur at high intensity due to limitations on the current output of the high-tension power supply. The saturation effect is more pronounced for large stimuli than for small ones and varies widely between different models of CRT, since beam current can often be sustained for small but not large stimuli. The beam current limitation raises the general principle that no single monitor calibration can be adequate for all possible stimuli and the calibration should use stimuli similar in average luminance to those that will be used in practice.

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 in Eq. (1). Gamma correction can be done in various ways [2].

Unfortunately, the simple gamma function is not a good fit for some monitors. Several alternatives have been proposed for such cases. Travis ([1], p. 155) proposed plotting the data on a double logarithmic plot (using natural logarithms) or performing a piecewise linear interpolation between each pair of measured points. Pelli and Zhang [3] suggest using a power law or, as an alternative, an eighth-order polynomial. They also suggest using interpolation because it can be easily and quickly implemented. In this paper, we have decided to used the Naka–Rushton equation [4] which is used in physiology because it provides an easy way of representing saturation at high luminances.

$$L = GD^{\gamma}/(D^{\gamma} + D_{50}^{\gamma}), \tag{2}$$

where G is the saturating luminance, D is the voltage and D_{50} represents the voltage at half-saturation.

2.2. Principle of visual calibration

We use a visual comparison to determine the parameters of the relationship between D and L. The observer was presented with two fields. The task was to adjust a voltage which was applied to all the pixels in one of these fields so that it matched the brightness of the other field in which a fraction Q of the pixels were illuminated by the maximum voltage and the remainder were unilluminated. Thus instead of measuring the luminance produced by a given voltage we measure the voltage which produces a given fraction Q of the maximum luminance. The DAC output (D) produces a luminance (L) that is a given proportion (Q) of maximum luminance ($L_{\max}$).

The equation that represents equal luminosity is

$$L = QL_{\max}. \tag{3}$$

By using this relationship it is possible to determine the calibration function from the relationship between D and Q in the same way as with a photometric calibration.

Smooth functions were fit to the values of Q and D using a least-squares method. The smooth curves were then used to estimate the function relating screen luminance to voltage. This function was then used to calculate lookup tables for linearisation. Sinusoidal and beat (sum of two sinusoids) luminance modulations were generated from the calibrated lookup tables and their profiles were measured with a photometer in order to check the calibrations.

2.3. Equipment

We used a Mitsubishi HL 7955 monitor with a refresh frequency of 120 Hz, controlled by a Cambridge Research Systems VSG 2/1 graphics card in an IBM-compatible 80386 computer. The signals from the three guns were

Table 1
Error sum of squares for split and flickering field comparisons with average and dark background for three observers (EC, MA and PS)

	Error sum of squares OBS EC	Error sum of squares OBS MA	Error sum of squares OBS PS
Flickering field average background	96.27	109.86	244.14
Split field average background	138.72	191.94	155.54
Flickering field dark background	828.57	263.81	2160.72
Split field dark background	328.08	190.58	540.34

attenuated and combined to produce finer resolution of contrast [3] and were used to drive the r, g and b display inputs in parallel.

The display was 512 by 512 pixels and subtended 10° square at the viewing distance of 1.71 m. The test field was 256 pixels by 256 pixels and consisted of two components. The first component was a patch of pixels whose driving voltage was varied by the computer, the second component was a horizontal rectangular wave grating in which the dark bars were unilluminated (approximately 0.1 cd. m^{-2}) and the bright bars were illuminated to the maximum voltage (approximately 95 cd. m^{-2}). The spatial period of the grating was 10 pixels (approximately 0.2°) and the duty cycle varied between 0.1 and 0.9. By using a horizontal grating (i.e. with the bars parallel to the display raster lines) we eliminate adjacent pixel dependencies caused by limitations in frequency response of the Z amplifier [5].

The two components of the test field were either presented side-by-side, each occupying half of the test patch, or were alternated temporally so that each occupied the whole test patch and they were exchanged 10 times per second to give a flicker rate of 5 Hz. The spatial structure of the two components of the test field was visibly different. One was spatially uniform whereas the other consisted of a horizontal grating with a spatial frequency of about five cycles/degree. This makes the subjects' task more difficult as it becomes a 'class B' observation in the terms of Brindley [6]: subjects are required to judge whether two visibly different stimuli have the same brightness. We could have converted the task into a 'class A' observation by using a diffuser to obscure the spatial pattern thereby reducingthe task to one of distinguishing whether the two patches of pixels were identical [6]. However, although this would almost certainly have made the results from each observer less variable we chose not to do so because we wanted to estimate the effectiveness of visual calibration under sub-optimal conditions more like those that would be encountered in real life with unsupervised and unskilled observers using a 'least effort' approach.

The driving voltage of the uniform patch of pixels was controlled by the computer in accordance with the subject's responses on three mouse buttons. One button served to increase the voltage, one to decrease the voltage, and the third to signal an acceptable match.

Luminances were measured using a UDT Model 61 photometer. For checking calibrations the spatially uniform test patch of pixels was modulated by the appropriate temporal waveform digitised to 1024 points and the analogue output of the photometer was read by the computer using a 12-bit analogue-to-digital converter mounted in a data acquisition card (Cambridge Research Systems AS-1). Using a temporal rather than a spatial pattern to test the calibration in this way makes it possible to use a standard photometer head that records the luminance over a substantial area of the screen rather than using a more elaborate travelling microscope arrangement to measure the luminance of individual lines or pixels. Ten readings were averaged for each data point and a Fast Fourier Transform routine was used to estimate the amplitude of the fundamental component of the luminance waveform and of its harmonics from the resulting array of 1024 datapoints.

2.4. Choice of method of performing the visual comparison

We allowed the observer to match the luminance of the two fields using a temporal or a spatial comparison. For the temporal comparison the fields were presented in the same area of the screen and alternated at 5 Hz to form a flickering field. The temporal frequency of 5 Hz was chosen because it is close to the peak of the temporal contrast function [7]. The observer's task was to adjust the DAC value to cancel the apparent flicker of the field. For the spatial comparison the two fields were presented side by side to form a single split field and the task of the observer was to change the DAC value to cancel the apparent luminance difference between the two sides of the split field.

Another variation in conditions we explored was to set the surround to the comparison field to be dark, or to be at the average of the monitor's minimum and maximum luminances. Combining the two comparison methods with the two different background conditions we have a total of four different conditions: split field and average background, split field and dark background, flickering field and average background and flickering field and dark background.

The grating patterns with different duty cycles give nine different proportions of illuminated pixels, from 0.1 to 0.9. Each comparison was repeated four times by each observer in each of the four conditions. Three observers made this set of measurements. For each observer and each condition we fit a Naka–Rushton equation and obtained the sum of squared errors. In Table 1, we show the sum of squared errors for each observer in each condition. The results obtained using dark backgrounds were consistently worse than those obtained using the average luminance background. On the average background similar results were obtained using temporal (flicker) and spatial (split field) comparisons. However, the task was easier and quicker for the observers when they used the split field. This is probably because in the temporal task where the observer is trying to find the voltage that produces minimum flicker the stimulus gives no indication of the sign of the change that will reduce the flicker. In the spatial task the observer can always tell whether the voltage needs to be increased because she can see which half of the display appears to be brighter. For this reason we selected the spatial comparison and the average background for our full evaluation of the visual calibration method.

2.5. Observers

We used a total of six observers including one author (EC). Although several of them were experienced in objective psychophysical tasks, none had any significant experience of making subjective visual comparisons. With the exception of EC they had no knowledge of the aims or background of the project. They performed the task using self-paced free viewing. Where appropriate they wore their prescribed spectacle correction.

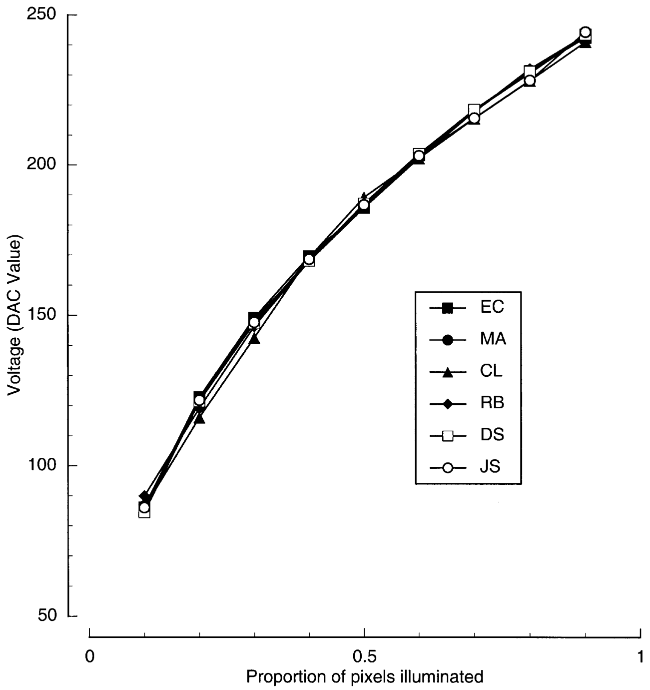

Fig. 1. Mean DAC settings made by six different observers to illuminate a uniform field of pixels to match a field of pixels in which different proportions of pixels are fully illuminated and the remainder are left unilluminated. Each symbol type shows the average of 10 settings of a different observer.

3. Results

3.1. Visual calibration

Six observers made split field matches, adjusting the voltage driving the pixels in a uniformly illuminated half field until it appeared to match a grating pattern in which a proportion of pixels were illuminated with the maximum voltage and a proportion were unilluminated. Matches were made to patterns in which the proportion of illuminated pixels varied from 0.1 to 0.9 and each set of matches was repeated 10 times by each observer.

Results show good agreement both within and between observers. Fig. 1 shows the mean settings for each of six observers plotted together. To examine the consistency within each observer's set of measurements we calculated the Pearson product moment correlation coefficient [8] between each set of matches of DAC values and the mean set for that observer. We obtained the lowest value ($r = 0.98$) with observer CL and the best ($r = 0.999$) with three observers (DS, EC and MA).

In order to assess how well different observers agree we calculated the Pearson product moment correlation coefficient between the mean values of each observer and the mean values over the six observers. We obtained a value higher than 0.999 for all observers.

Each set of measurements was transposed to give a plot of the proportion of pixels illuminated against the matching DAC voltage. Best-fitting parameters of Naka–Rushton equation were fit to the transposed measurements using a least-squares method, and used to estimate the function relating screen luminance to voltage. This procedure was done both for individual sets of matches from each observer (the first and the last set), for the whole block of 10 sets of matches, and for a block of four sets of matches. Fig. 2 shows representative results from two observers (DS and CL) who made the measurement with the lowest and the highest dispersion. Note that they have the positively accelerated form of a typical CRT gamma function (see for example Fig. 5.1 on p. 156 of Travis [1]).

3.2. Checking the calibration

The different calibration functions were used to calculate lookup tables which were used to generate two kinds of luminance modulations, sinusoidal and beat patterns, to check fidelity and reproducibility. Photometric measurements of the luminance profiles were made and a FFT was used to estimate the mean luminance, the contrast and the relative amplitude of components arising as a result of distortion-harmonics of the single sine-wave and difference and sum frequencies of the components of the beat pattern. This gives a basis for comparison of visual and photometric calibrations.

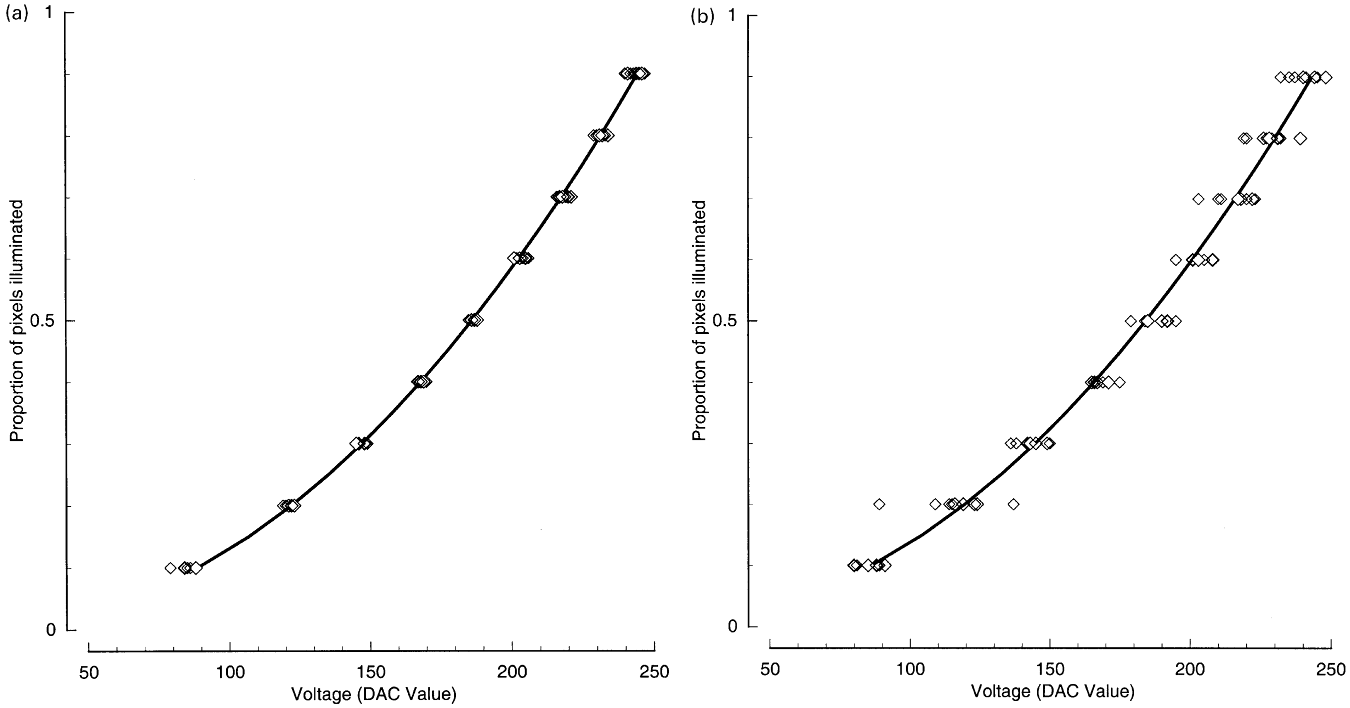

Fig. 2. Experimental data and the best fitting curve for: (a) observer DS and (b) observer CL.

3.3. Sinusoidal luminance profiles

To check the visual calibration, we generated sinusoidal luminance modulations (containing one cycle in 1024 points) of seven different nominal contrasts: 1, 0.3, 0.1, 0.03, 0.01, 0.003 and 0.001, using data from photometric and visual calibration and using an uncalibrated linear ramp. These modulations were measured by a photometer connected to an analogue-to-digital converter, and a Fast Fourier transform was used to calculate the mean luminance and the amplitude of the wave form, and of its first few harmonics.

Fig. 3 shows the measured contrast plotted against the nominal contrast using photometric and visual calibration and the uncalibrated linear ramp. The measured contrast was given by the magnitude of the fundamental component divided by the mean luminance. Fig. 5a shows results for three different observers, EC, MA and CL, based on average data from 10 repetitions. The results using photometric and visually calibrated corrections are almost the same and are very different from the uncalibrated case, except that for the curve corresponding to the observer EC there is a deviation at the lowest contrast.

Fig. 3b compares the visual calibrations based on different groups of measurement by the observer whose settings showed the highest dispersion (CL). The five different curves correspond to three calibrations one based on the average of 10 sets of measurements, two more based on the first and the 10th set, the photometric calibration and the uncalibrated linear ramp. The results are similar to Fig. 3a except that for the curve based on the 10th set of measurements there is a deviation at the lowest contrasts.

Fig. 3c compares three visual calibrations performed by a single observer (MA) using the average of 10 sets of measurements, the average of the first four sets of measurements and the first set of measurements, with the photometric calibration and the uncalibrated linear ramp. The results are similar to Fig. 3a but again there is a slight deviation in the case of the visual calibration based on a single set of measurements.

The general conclusion from the similarity between the curves based on photometric and visual calibration and their difference from the curves based on uncalibrated displays in Fig. 3 is that visual calibration is effective in producing the correct contrast, particularly at contrasts of 0.01 and higher. Although there are substantial deviations at contrasts close to 0.001 this is hardly a surprise as these are close to the limits of visibility and of the stimulus generating equipment. It is however clear from Fig. 3 that better results are obtained when several sets of measurements are averaged.

As a check of the effectiveness of visual calibration in ensuring the fidelity of the image we tested the sinusoid for second harmonic distortion. Fig. 4 shows the second harmonic contrast expressed as a proportion of the contrast of the fundamental, plotted against the intended contrast of the fundamental. It contains plots for photometric and visual calibration and for the uncalibrated linear ramp. Fig. 4 a–c are based on the same calibration data as Fig. 3 a–c, respectively.

In a perfectly calibrated display there would be no second harmonic distortion. This is more or less true for contrasts

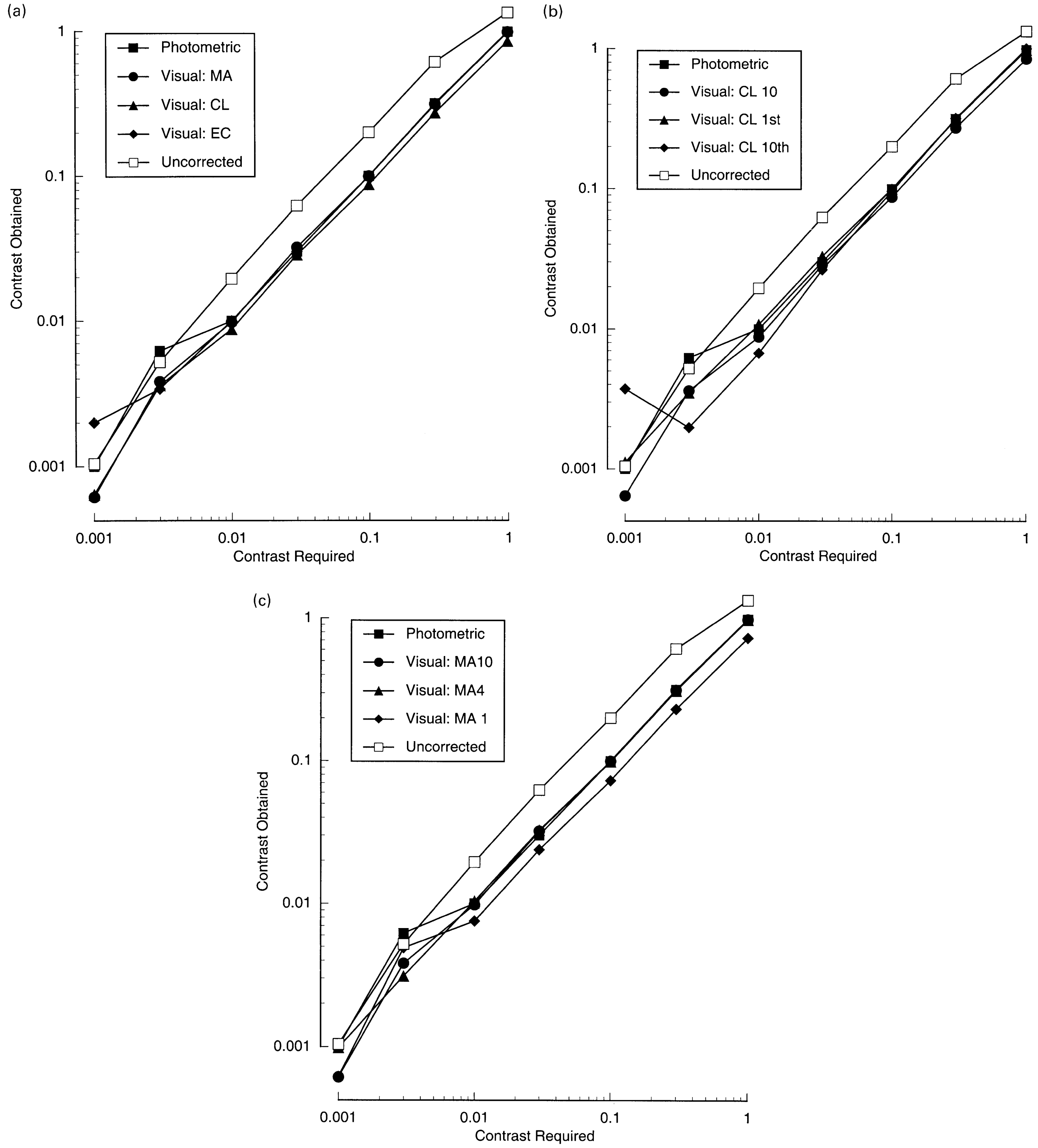

Fig. 3. Contrast obtained vs contrast required in sinusoidal luminance modulations generated using photometric calibration, visual calibration and the uncalibrated linear ramp. (a) Visual calibrations are based on average data from 10 repetitions for three observers (EC, MA and CL), (b) visual calibrations are based on the average of 10 sets of measurements, and on the first and the 10th set for one observer (CL), (c) visual calibrations are based on the average of 10 sets of measurements, the average of the first four sets of measurements and the first set of measurement for one observer (MA).

between 0.01 and 1 both for the display based on photometric calibration and for those based on visual calibration, whereas the sinusoid produced without calibration had a large second-harmonic component at high contrasts. In Fig. 4a, it can be seen that in all cases the averaged visual calibration produces a similar pattern of results to the photometric calibration over the range for contrasts above 0.04. Fig. 4b and c show again that better results are obtained with

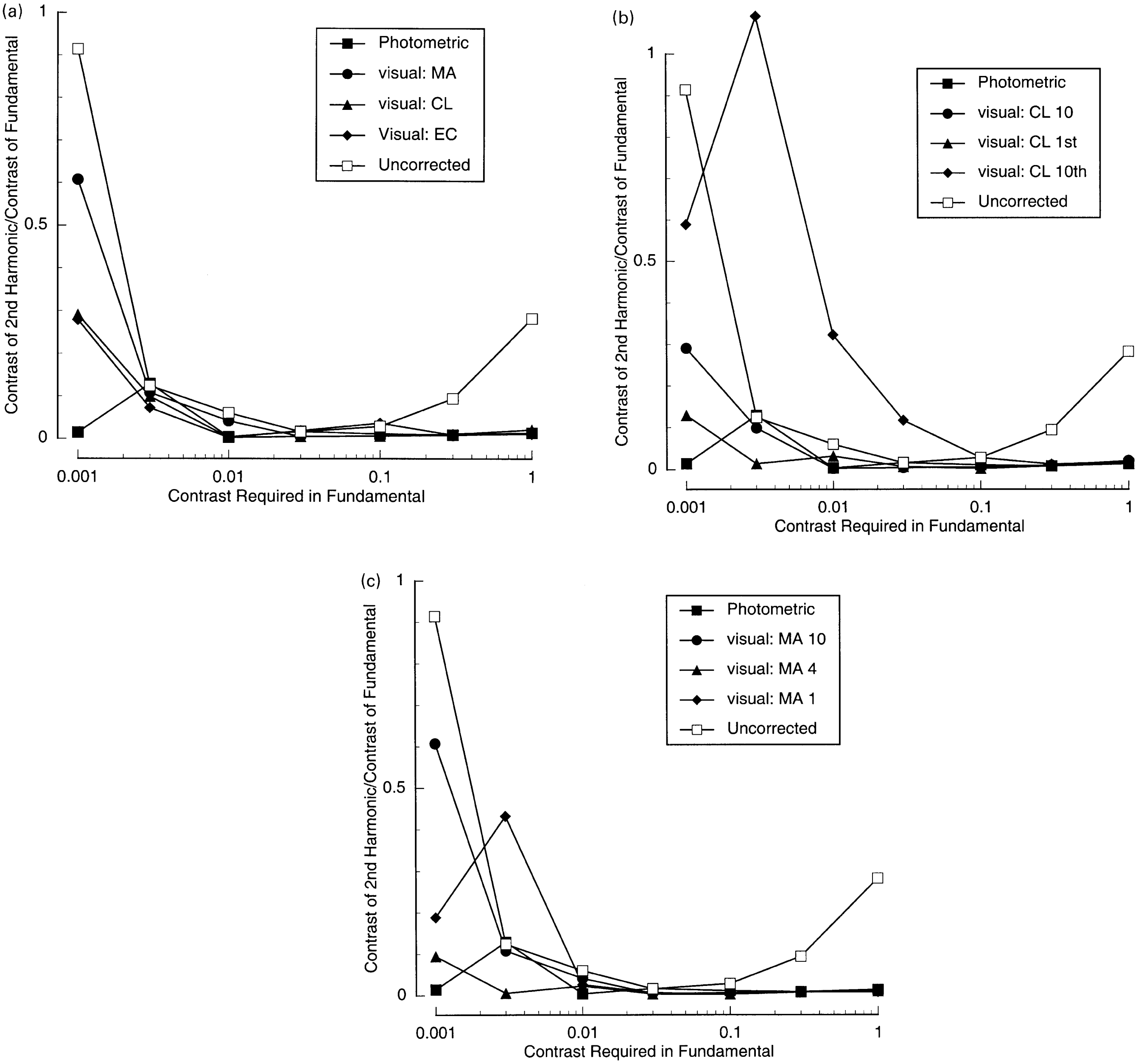

Fig. 4. Second harmonic amplitude expressed as a fraction of the fundamental amplitude plotted against the required contrast of sinusoidal luminance modulations generated using photometric calibration, visual calibration and the uncalibrated linear ramp. (a) Visual calibrations are based on average data from 10 repetitions for three observers (EC, MA and CL), (b) visual calibrations are based on the average of 10 sets of measurements, and on the first and the 10th set for one observer (CL), (c) visual calibrations are based on the average of 10 sets of measurements, the average of the first four sets of measurements and the first set of measurement for one observer (MA).

visual calibration when several sets of measurements are averaged than when a single set is used alone.

In the next set of measurements, we use a beat pattern which provides a more sensitive test of the effectiveness of the calibration for removing distortion from the display.

3.4. Distortion in beat waveforms

A beat pattern, made by adding together two sinusoids, provides a sensitive test of the simplest forms of distortion likely to occur in poor gamma correction, since the distortion generates components with a frequency that is the difference between the frequencies of the components. A variety of difference-frequency phenomena have been used to infer the existence of non-linear processes in the human visual system, so it is important to be able to avoid generating difference frequencies inadvertently [9–16].

We used a 1024 point beat waveform that was the sum of sinusoids containing four and five periods. We use the

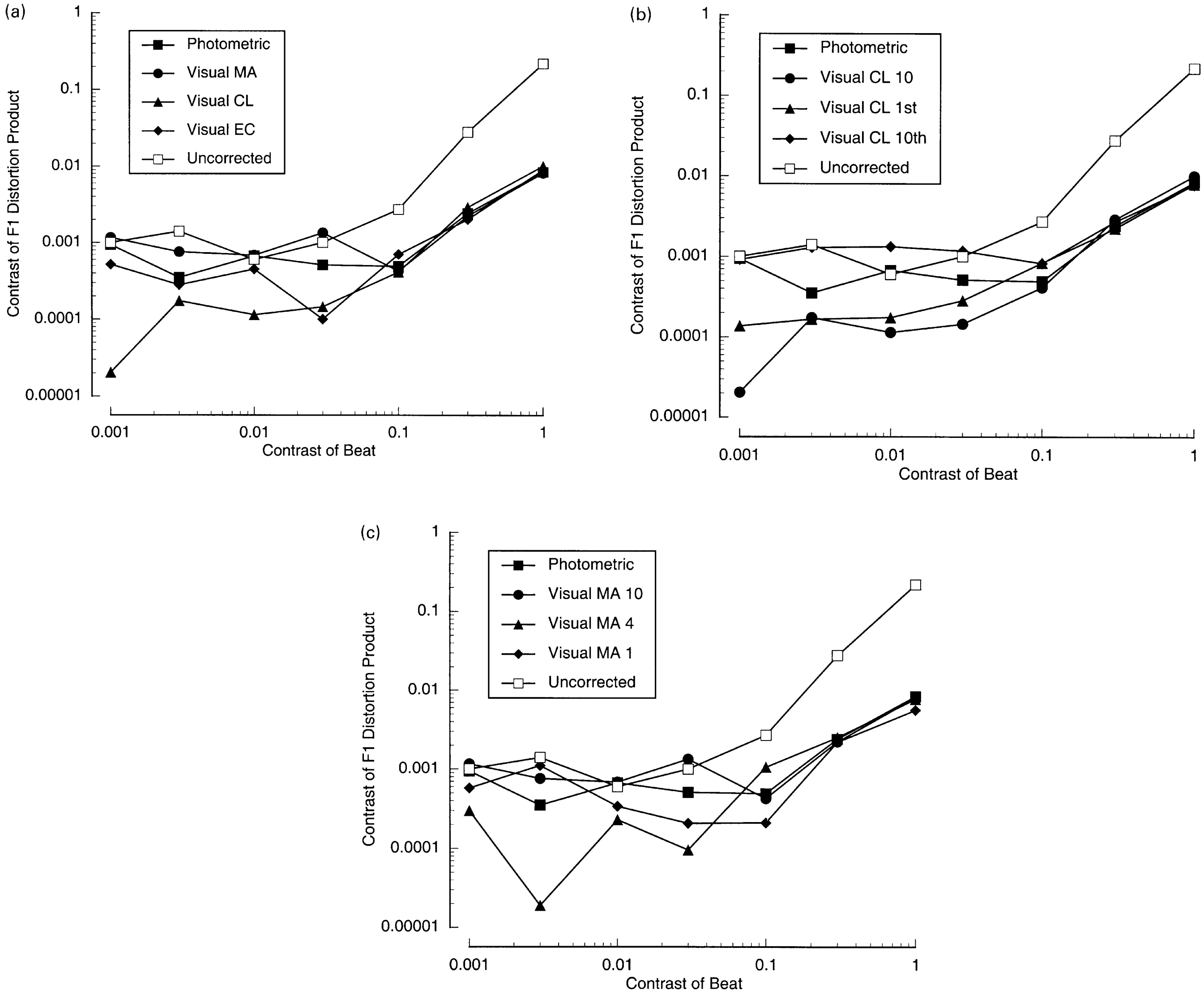

Fig. 5. The magnitude of the difference-frequency distortion product as a function of the contrast of a beat modulations generated using photometric calibration, visual calibration and the uncalibrated linear ramp. (a) Visual calibrations are based on average data from 10 repetitions for three observers (EC, MA and CL), (b) visual calibrations are based on the average of 10 sets of measurements, and on the first and the 10th set for one observer (CL), (c) visual calibrations are based on the average of 10 sets of measurements, the average of the first four sets of measurements and the first set of measurement for one observer (MA).

same procedure as above to measure the magnitude of the component at the fundamental frequency, which should be zero.

Fig. 5a–c show the magnitude of the distortion product plotted as a function of the contrast of the beat. The data are obtained from displays generated using photometric and visual calibrations and the uncalibrated linear ramp. Fig. 5a shows results for three different observers, EC, MA and CL, based on average data from 10 repetitions. Fig. 5b compares the visual calibrations based on different groups of measurement by the observer whose settings showed the highest dispersion (CL). Out of these three visual calibrations, one is based on the average of 10 sets of measurements and the other two are based on the first and the 10th set. Fig. 5c compares three visual calibrations performed by a single observer (MA) using the average of 10 sets of measurements, the average of the first four sets of measurements and the first set of measurements.

All the calibrated displays show a similar pattern of results. When the contrast of the pattern is 0.1 or less the contrast of the distortion product is about 0.001 which would be undetectably low. As contrast rises to a maximum the distortion product contrast rises to about 0.01, which should be clearly detectable. This rise is very similar in all the calibrated displays whether they are based on single or multiple visual calibrations or on photometric calibration. In the uncalibrated display, the distortion product is about 10 times as high as in the calibrated displays.

4. Discussion

The reliability of the visual calibration procedures is indicated by the fact that under the best circumstances, when several sets of measurements are averaged it gives similar results to those obtained using a photometer. With a good observer making measurements carefully even a single set of measurements, which can be done in about 5 min, reduces distortion by at least a factor of 10. In principle, it would be possible to optimise the efficiency of the calibration procedure by estimating the reliability of the observer by repeating a small number of measurements and then increasing the number of repeats to produce an acceptably small standard error.

It would also have been possible to optimise the spatial distribution of unilluminated and illuminated pixels in the test patch. We used a horizontal test pattern which substantially eliminates contrast loss caused by adjacent pixel nonlinearities. However, the bright and dark pixels formed a regular, clearly visible pattern, a rectangular-wave grating of spatial frequency five cycles/degree. We would expect that more reliable matches could be made if the spatial structure were less regular or less visible (for example it could have been covered by a diffuser). However, this would carry with it the potential disadvantage that the testing situation becomes more complicated, which would be inconvenient in some possible applications. Thus the results here can be regarded as the worst case. They indicate what can be achieved when the pattern is highly visible.

Even so, the results indicate that visual calibration is sufficiently reliable to be used as an alternative to calibration using a photometer. It is easier and cheaper than using a photometer: a good photometer can be more expensive than the combined cost of the computer, graphics card and monitor.

5. Conclusion and precautions

Visual calibration of a CRT display is not only cheaper than using a photometer, but also much simpler, and may be particularly useful in contexts where visual testing is to be done by non-technical personnel. The following precautions may be important in obtaining good results:

1. Test and comparison patches for the calibration judgement should abut.
2. Calibration patches should occupy only a small fraction of the screen (25% in our case) to avoid power-supply overload.
3. Adjacent pixel nonlinearities can be avoided by using test patterns that contain only horizontal lines. In principle they could be measured by comparing horizontal and vertical patterns.
4. Several estimates should be taken for each data point unless the observer is known to be reliable.

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