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# Psychophysical contrast calibration ☆

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ABSTRACT

Electronic displays and computer systems offer numerous advantages for clinical vision testing. Laboratory and clinical measurements of various functions and in particular of (letter) contrast sensitivity require accurately calibrated display contrast. In the laboratory this is achieved using expensive light meters. We developed and evaluated a novel method that uses only psychophysical responses of a person with normal vision to calibrate the luminance contrast of displays for experimental and clinical applications. Our method combines psychophysical techniques (1) for detection (and thus elimination or reduction) of display saturating non-linearities; (2) for luminance (gamma function) estimation and linearization without use of a photometer; and (3) to measure without a photometer the luminance ratios of the display's three color channels that are used in a bit-stealing procedure to expand the luminance resolution of the display. Using a photometer we verified that the calibration achieved with this procedure is accurate for both LCD and CRT displays enabling testing of letter contrast sensitivity to 0.5%. Our visual calibration procedure enables clinical, internet and home implementation and calibration verification of electronic contrast testing.

## 1. Introduction

Visual psychophysical laboratory studies are usually conducted using electronic displays. In the clinic, electronic displays have been replacing the paper wall chart and optical projector tests of visual acuity and contrast sensitivity (CS) measurements starting with the 1980s introduction of the B-VAT system (Mentor O&O, Norwood, MA) (Williams et al., 1980). Electronic clinical test systems are in widespread use today (e.g. TestChart 2000 (Thomson Software Solutions, UK), Metrovision (Metrovision, France), Smart-System20/20 (M&S Technologies, Skokie, IL) and CST1800 (Stereo Optical Co, Chicago, IL)). Following the development of the basic electronic visual acuity chart many other clinical tests were incorporated into these systems including letter and grating CS in the B-VAT II-SG (Corwin, Carlson, & Berger, 1989) followed by a battery of binocular vision tests (Waltuck, McKnight, & Peli, 1991) that included distance stereoacuity testing (Rutstein & Corliss, 2000; Wong, Woods, & Peli, 2002). Many personal-computer based clinical vision test systems are now marketed either as integrated systems or as software packages to be used with existing computers and displays. In addition to the use in clinics, there has been a growing trend for remote visual testing using home computers (Dagnelie et al., 2003, 2008), smart phones, tablets (Dorr et al., submitted for publication), and over the Internet (Dagnelie, Zorge, & McDonald, 2000; Lavin, Silverstein, & Zhang, 1999). In-home testing has potential benefits in reducing costs, increasing convenience, recruitment of subjects for studies, monitoring of patients, and the ability to collect data frequently. However, home testing presents more challenges to standardization, display characterization and calibration.

The growing popularity of clinical letter CS testing using paper charts (e.g., Pelli–Robson chart (Pelli, Robson, & Wilkins, 1988), Reagan chart (Regan, 1988), and the Mars charts (Arditi, 2005; Dougherty, Flom, & Bullimore, 2005)) lead to the incorporation of letter CS testing in most clinic electronic vision test systems. While testing of visual acuity, stereo-acuity and other binocular functions is not very sensitive to chart or display luminance calibration, the testing of (letter) CS requires accurate luminance calibration of the display and, in most cases, higher luminance resolution than available with typical 8-bit displays and graphic cards. The enhanced luminance resolution is required to enable presentation of contrast levels near and below the human threshold for detection. A luminance calibration system with enhanced luminance resolution was provided with the early B-VAT II-SG that measured both letter CS and detection thresholds of sinusoidal gratings using only 6 bits of native luminance resolution. That system required a manual adjustment of display "brightness" to specific luminance values as measured with a photometer, as well as a flicker minimization (visual psychophysical) method to match the mean luminance of

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gratings in the two hardware-modified domains of the expanded dynamic range. The difficulty associated with such calibration is further exemplified by the contemporary TestChart 2000 that recommends a proprietary light meter for calibration that can be either bought or rented from the manufacturer. A number of commercially available lab systems, such as the Cambridge Research Systems ViSaGe (Cambridge Research Systems Ltd., UK), come equipped with a photometer to facilitate a system calibration. Thayaparan, Crossland, and Rubin (2007) compared the TestChart 2000 to the Pelli–Robson and Mars charts and found that the coefficient of repeatability was 0.18 for the Pelli–Robson chart, 0.12 for the Mars chart, but only 0.24 log units for TestChart 2000. In addition, they found that the TestChart 2000 did not agree well with the Pelli–Robson chart which they attributed to the performance of LCD monitors at low contrast levels. They did not make any explicit statements as to which of these was the most accurate.

Most psychophysical studies involving electronic displays and manipulation of electronic images require accurate calibration of the display so that the luminance characteristics of the displayed images are known. Usually this is done by linearizing the relationship between the digital pixel representation and the luminance of the display (Brainard, 1989; Brainard, Pelli, & Robson, 2002). Historically, such studies were conducted using CRT displays and accurate and expanded luminance resolution was possible by combining the three color outputs of the graphic cards through a resistors net (video attenuator) to expand the luminance resolution of monochrome CRTs (Dakin et al., 2011; Falkenberg, Rubin, & Bex, 2007; Li et al., 2003; Niebergall, Huang, & Martinez-Trujillo, 2010; Pelli & Zhang, 1991; Watson et al., 1986). Calibration and linearization of such systems requires photometric measurement of the display voltage to luminance relations (the gamma function) followed by photometric verification of the successful calibration (Swift, Panish, & Hippensteel, 1997).

A linear luminance to digital image relationship is also required for many studies that can be safely conducted within the limited 8-bit display range (Haun, Woods, & Peli, 2012; Vera-Díaz, Woods, & Peli, 2010; Webster, Georgeson, & Webster, 2002). The same is true for most studies of image processing and image quality. If calibrations are not performed the impact of the display's non-linear voltage (pixel-level) to luminance gamma function may drastically affect the content of the displayed images (Peli, 1992a).

The quantization of luminance levels in electronic displays is particularly problematic at low luminance levels, where a change from one pixel value to the next pixel value produces a change in luminance that is a large fraction of the prior luminance. Thus, producing fine gradations of low contrasts on dark backgrounds is difficult or impossible (this limitation affects printed charts similarly). Therefore, paper charts and computer-based contrast sensitivity tests use gray letters on bright backgrounds. Note that the need to linearize the display may result in reduction of the dynamic range, as most linearization methods result in fewer available gray levels thus reducing the available dynamic range and reducing the luminance resolution below the original 8-bit depth. The resulting limited luminance resolution (about 6 bits) is insufficient to challenge human contrast sensitivity even at the bright end of the luminance range. The contrast generated with pixel values of 254 and 255 as the low and high luminances is easily detected by a normally-sighted observer, as the accelerating gamma function produces a ratio between these luminances that is higher than the pixel-value ratio suggests. The problem is even worse when we attempt to generate sinusoidal or Gabor patches since one has to operate near the middle of the display luminance range where every gray level step represents a higher fraction of the mean luminance or a larger change in contrast and where it may be necessary to generate a sinusoidal variation near this luminance over a spatial extent of at least 6 pixels (Pelli & Zhang, 1991; Woods, Nugent, & Peli, 2002).

CRT displays are rapidly disappearing from the consumer markets and are being replaced by LCD monitors. LCDs have the advantages of higher luminance, a larger color gamut (Sharma, 2002), and larger screen sizes. Offsetting these advantages are the disadvantages of more complex luminance response functions that may result in larger calibration errors (Sharma, 2002), the inability to use voltage-based luminance resolution expanders and strong sensitivity to viewing angle. If electronic displays are to be used clinically it is now necessary to be able to calibrate LCD screens.

We present a psychophysical display calibration procedure that enables (1) detection and elimination of display saturating non-linearity; (2) luminance calibration (linearization); and (3) measurements of luminance ratios of the three color channels (used in the color bit-stealing technique for luminance resolution expansion (Tyler, 1997a)), all *without use of a photometer*. This calibration approach can facilitate letter CS and other testing in the clinic, over the internet and at home.

## 2. Display saturating non-linearity detection and elimination

Electronic displays frequently have a saturating non-linearity at the bright end of the luminance range or a cut-off at the dark end. In a display with a saturating non-linearity, the luminance curve levels off prior to the digital input reaching the minimal or maximal RGB values. This saturating non-linearity reduces the number of unique grayscale shades displayable and further complicates the calibration process. This is particularly true in calibration procedures that fit a gamma function. The region of saturating non-linearity (high luminance) occurs where we most often test the limits of the contrast sensitivity of the visual system. A saturating non-linearity may occur in individual color channels (Fig. 1A). Though the calibration method in Colombo and Derrington (2001) accounted for saturating non-linearity, it did not include a procedure to detect whether saturating non-linearity occurred or a method to reduce or eliminate it. It is preferable to ensure that the display is not saturated before initiating a calibration process, as the saturation also limits the available dynamic range.

We used the pattern shown in Fig. 1B to visually detect saturating non-linearity at maximum luminance. The background consisted of four rectangular regions (gray and individual primary colors), each near its maximum level. Each bar had 8 square patches, arranged in decreasing order of luminance.[1] If all 8 patches in each bar were visible, there was no saturating non-linearity and the procedure continued to the next step. If any of the brighter patches were invisible, the observer adjusted the physical or software settings on the display, including brightness, contrast, and color profile until the patches with lowest-contrast/brightest-luminance (right most) became just visible. This procedure simultaneously ensured that there was no saturating non-linearity in any of the color channels.

The same procedure was repeated for low luminances, to control for cut-off, using a similar stimulus prepared for that range. At that end, the dimmest square patches would be indiscriminable if there was cut-off. At the end of the process, all test patches had to be visible simultaneously at both the high and low end luminances of the display. The display settings that achieve that were then locked (if such locking was provided by the display) and recorded for future experiments. The cutoff at the low end is often

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[1] In a pilot experiment, we determined the best increments (on our displays) for the saturation test bars as follows: For the bright background: for grayscale, pixel-value increment = 2 (e.g. the squares were 253, 251, 249, etc.). For the color patches, the increments were green = 3, red = 4, blue = 5. For the dark background: grayscale increment = 3, all colors increment = 5.