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Calibration Tools for PC-Based Vision Assessment

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Abstract— **This paper details the research and development of the PC Vision system, a unique calibration and monitoring subsystem that will enable use of personal computers as accurately calibrated and controlled vision test instruments. The need for such a system is evident. Display intensity and chromaticity, test distance, room illumination, and a number of other variables must be controlled to avoid unexplained discrepancies in test outcomes, within and between individuals and test locations. Modern displays (CRT-, LCD-, or projector-based) have sufficient resolution, gamut, and stability to allow high-quality stimulus presentation. The PC Vision system consists of two categorical functions— one to calibrate screen properties, the other to monitor room and test setup conditions — packaged into a fully integrated hardware prototype.**

I. Introduction

FOR over 10 years, researchers have designed software to use PCs for high-quality vision testing. A CVNet posting from June 1995 [1] listed several software packages designed by university researchers, as well as 3 designed by commercial entities. However, only one of these, Keeler Ltd, made (acuity and nystagmus) tests running on standard PCs (which at the time lacked the specs for high-quality stimuli), while the other two, NeuroScientific and Cambridge Research Systems [2], as well as one university research group in Oslo, designed software to run on dedicated high-quality hardware. More recently, Bach *et al*. [3,4,5] produced visual acuity, stereo acuity, and contrast sensitivity testing, jointly available as the Freiburg vision tests, initially for Mac, but currently also for PC. This test software uses efficient psychophysical algorithms and includes some data management.

Furthermore, several companies sell vision test software, sometimes in combination with the (standard) computer system on which it is run, and accessories such as a remote keypad to operate the tests. Examples are AcuityPro software by VisionScience [6] ($1,395), Snellen acuity and FM-100 hue test by LittleBits Multimedia [7] (freeware), a set of color vision tests by Visual Mill [8] ($29 download), aneisikonia tests by Optical Diagnostics [9] ($399), and a broad series of tests marketed to doctors, DMVs, employers, and schools by VisionRx [10] (unspecified purchase price, or per-use fees). With few exceptions, the test software is not particularly sophisticated, and can be classified as computer-assisted rather than automated. It is difficult to assess how widely these tests are being used by eye care providers and vision screeners, but very few appear to be used for research purposes, or meet the necessary quality standards.

Dagnelie *et al*. [11] were the first, to our knowledge, to publish results of a clinical trial where PC-based test results were used as an outcome measure (in fact the only outcome measure). In a subsequent trial [12], the same group used a much broader set of PC-based vision tests, performed weekly on the subjects' PCs as secondary measures in addition to lab-based vision measures collected at 6 week intervals. It appears that wider development and use of high-quality PC-based vision tests is stymied by the lack of convenient and reliable calibration equipment and methods.

The PC Vision device was conceived in response to this need for an integrated yet modestly priced subsystem that can reliably and accurately perform a number of important calibration and monitoring functions for computerized vision tests using CRT and LCD displays. The concept is to make a self-checking, fully automated calibration system that requires no outside input or expertise to run, just a guarantee that the conditions for the vision test are relatively the same independent of the testing site. The paper is organized as follows. The Methods section describes the features that are to be measured by such a system and how to achieve them. In the Results & Discussion section, we report on experimental data and comment. For the Implementation and Operation sections, the hardware of the system is concisely summarized and a test scenario is demonstrated, respectively. And finally, the paper is concludes with suggestions for future research.

II. Methods

In order to provide monitor calibration we developed a small instrument that combines 5 measurement functions: pixel size, chromaticity values, gamma function(s), background illumination, and patient distance.

A. Pixel Size

To measure pixel size on the screen, three photo sensors (electronic circuits with photodiodes or photo transistors as the light-capturing element) are placed in an equilateral

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triangular configuration with sides of 50.0 mm. Knowing that the detectors are separated by 50.0 mm allows us to write the following equations for the horizontal and vertical pixel sizes dx and dy (in mm):

$$(x_i - x_j)^2 * (dx)^2 + (y_i - y_j)^2 * dy^2 = 50^2$$
$$(i, j = 1,2,3; i \neq j) \text{ (1)}$$

Each photo sensor will be recording screen luminance through a tubular aperture with 0.1 mm² area and 5 mm length, as shown in Fig. 1. This arrangement provides the sensor with the integrated light output of a circular screen area with a diameter of 0.36 mm, similar to the size of a single screen pixel on a typical 17" monitor. The narrow opening angle of 4 degrees provided by the tube is needed to limit the effect of screen thickness in a CRT, where the glass of the vacuum tube separates the phosphor from the diode aperture. The triangular arrangement allows for pixel size calibration regardless of the orientation of the calibration box on the screen. The TAOS TSL238D sensor was used for these measurements [13].

Fig. 1. Triangular configuration for pixel size measurement.

B. Gamma Values

This feature is a measurement of the luminance output of the screen as a function of the nominal brightness value sent out by the display adapter—for each phosphor. Typically this curve is not linear and the application can apply the inverse to get more linear displayed brightness and contrast. To measure the gamma value, the following power-law transformation is used where s and r is the input and output intensity level respectively:

$$\text{r} = cs^{\gamma} \text{ (2)}$$

In this expression c is a simple conversion factor and the input intensities are the digital scale values from 0 to 255. The gamma value γ specifies the power law characteristic of the relation. The gamma values as well as the next two features are estimated with the TAOS TCS 230 sensor allowing red, blue, green, and white light to be measured separately [13].

C. Chromaticity

Chromaticity measurements provide the color of the screen phosphors in CIE coordinates [x, y, Y]. Fig. 2 shows these chromaticity coordinates obtained for typical CRT and LCD screens with a Minolta CS-100. The tristimulus values are the amount of red, green, and blue in a color denoted [X, Y, Z]. The coordinates x and y specify the location of the stimulus in the CIE chromaticity diagram after normalizing with the summed tri-stimulus values [14], e.g.

$$x = \frac{X}{X+Y+Z} \text{ (3)}$$

By converting the [x, y, Y] to [X, Y, Z] and forming a matrix S with these tristimulus values in columns representing the screen primaries, and forming a second matrix D whose columns are the detector output triplets D = [Dr, Dg, Db] for the screen primaries, we can solve the

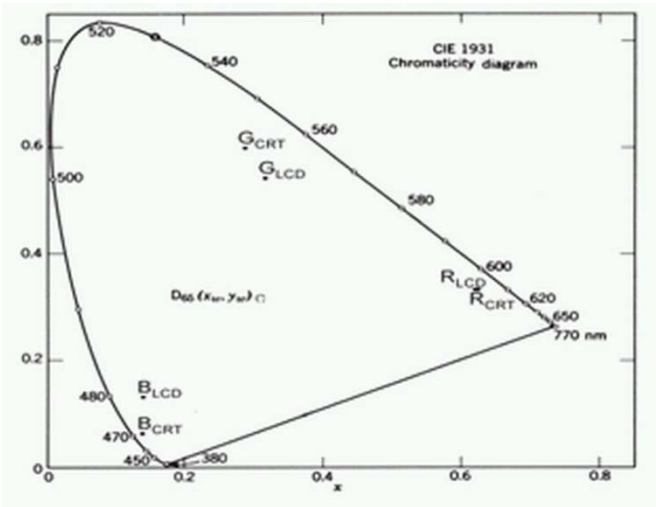

Fig. 2. CIE chromaticity diagram with CRT and LCD primaries for typical screens in our laboratory.

matrix equation $S = M * D$ by right multiplication with the inverse of D, D^{-1}, which yields:

$$M = S * D^{-1} \text{ (4)}$$

i.e., the relation matrix between the two vector spaces.

D. Ambient Light

The conditions of the room can be measured through two sensors. One sensor measures potential sources of screen reflection by accepting only a narrow cone of incident directions while the other measures the overall brightness (averaged intensities of light) in the room achieved through placing an opaque diffuser surrounding the sensor. Using these measurements, an operator can be instructed on whether the amount and distribution of light needs adjustment.

Chromaticity might also be a way to characterize the source of light (fluorescent, halogen, etc…). To examine whether the TCS 230 sensor might be adequate for this purpose, we conducted several lighting measurements, recording reflected light off a white sheet of paper at the location of the screen.

E. Distance Monitoring

Ultrasonic range measurement could provide a highly effective tool for measuring distance between the subject and the stimulus display as shown in Fig. 3. While there are other range-finding methods available today, this one is particularly well suited for the task since it is minimally invasive and does not require the use of lasers or other hazardous/intrusive devices. The apparatus essentially works like a sonar system: It emits an ultrasound pulse, waits for the echo to return, and calculates the distance on the basis of flight time and sound velocity. The device is capable of detecting a spread-out view as the sound waves propagate out and return. Depending

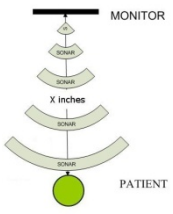

Fig. 3. Measurement of the distance from the patient to the monitor using ultrasonic range

on the exam room setup this may require some adjustment to avoid spurious echoes off nearby walls, etc. Max Botix's LV-EZ1 Max Sonar was selected for this purpose [15].

III. Results & Discussion

A. Pixel Size & Gamma Values

Table 1 provides reproducibility data for 13 screens, tested by 3 different subjects. Using (1), each pair of the 3 equations (one for each pixel sensor) yields values for dx and dy. As these columns show, two screens (LCD 1 and CRT 2) had unusual variability, and examination of the data showed that each of these screens had a substantially abnormal measure during one of the tests; we further determined that these two screens, unbeknownst to their regular users had a synchronization problem when displaying small bright stimuli on an otherwise dark screen, a condition that can certainly occur during vision testing. **We thus detected that careful calibration procedures can reveal screens that should not be accepted for vision testing.** The full calibration takes less than 30 s.

The last two columns also show that with one exception all gamma values were repeatable within 2.5%. This means that contrast values of low contrast stimuli can be calculated with high precision; it also means that very small contrast steps can be presented accurately by dithering with neighboring grey scale values.

TABLE 1
PIXEL SIZE, AND GAMMA VALUES OBTAINED ON 3 LCD AND 10 CRT SCREENS AT 1024 X 768 RESOLUTION

	dx (mm)			dy (mm)			gamma	
	mean	SD	CoV	mean	SD	CoV	mean	CoV
LCD 1	0.342	0.023	6.7%	0.411	0.026	6.3%	2.14	0.2%
LCD 2	0.385	0.014	3.7%	0.403	0.004	1.1%	2.34	0.4%
LCD 3	0.372	0.005	1.2%	0.386	0.003	0.8%	2.25	0.9%
CRT 1	0.296	0.000	0.1%	0.303	0.000	0.0%	2.81	1.4%
CRT 2	0.368	0.113	30.8%	0.259	0.084	32.3%	1.68	2.3%
CRT 3	0.291	0.000	0.0%	0.295	0.000	0.0%	2.05	0.2%
CRT 4	0.340	0.006	1.8%	0.352	0.001	0.4%	3.05	0.8%
CRT 5	0.300	0.003	0.9%	0.300	0.000	0.1%	2.47	0.1%
CRT 6	0.322	0.004	1.2%	0.355	0.002	0.6%	3.10	3.7%
CRT 7	0.302	0.001	0.2%	0.307	0.000	0.1%	2.38	1.2%
CRT 8	0.343	0.000	0.0%	0.348	0.000	0.1%	2.67	0.9%
CRT 9	0.310	0.002	0.6%	0.314	0.000	0.1%	3.49	0.4%
CRT 10	0.307	0.007	2.2%	0.348	0.011	3.2%	2.83	0.0%
Mean CoV			3.8%			3.5%		1.0%
Mean CoV exc.L1/C2			1.1%			0.6%		0.9%

B. Chromaticity

Tables 2 & 3 show the (x,y,Y) chromaticity coordinates obtained for typical CRT and LCD screens with a Minolta CS-100 meter and for the TCS230 light to frequency converters, respectively. The digital output level for the TCS230s is set at 255 for the R, G, and B channels of the display denoted (Dr, Dg, Db).

Table 4 gives the elements of M calculated from (3) for typical data in Tables 2 & 3. There are obvious discrepancies between the two matrices, particularly in the ratio of the diagonal elements, probably related to the relatively higher long-wavelength emissivity of the LCD screen, differences in green and blue primaries for the two screens, and substantial overlap between the green and blue detector responses.

TABLE 2
TCS230 AMBIENT ILLUMINATION TEST DATA FOR A CRT

CRT	x	y	Y	Dr	Dg	Db
R	.621	.327	14.1	327	75	43
G	.290	.597	69.7	132	1195	590
B	.146	.065	9.0	56	247	1392

TABLE 3
TCS230 AMBIENT ILLUMINATION TEST DATA FOR A LCD

LCD	x	y	Y	Dr	Dg	Db
R	.615	.331	16.4	194	66	34
G	.316	.543	48.1	95	576	289
B	.149	.134	12.4	30	204	640

TABLE 4
RESULTANT RELATIONAL MATRICES

Mcrt			Mlcd		
1.08	0.33	-0.07	1.41	0.46	0.06
0.35	0.92	-0.08	0.33	0.86	-0.19
0.04	-0.30	1.21	-0.01	-0.22	1.12

C. Ambient Illumination

The results for several ambient light conditions are shown in Table 5. The higher red content in the halogen light (compared to both sources of fluorescent lighting) is seen in the ratio of Dr to Dg and Db values in the TCS230 output. We conclude that the color should be considered to measure ambient illumination. In addition, the detector should be covered with a Hoya CM500 filter to approximate the human photopic sensitivity curve; such a filter can be found here [16].

TABLE 5
TCS230 AMBIENT LIGHT MEASUREMENTS

TCS230 sensor	Dr	Dg	Db	white
room	84	210	149	531
fluorescent	177	367	282	958
halogen	158	249	163	665
room+fluorescent	259	586	437	1493
room+halogen	234	445	305	1157

D. Distance Measurements

The MaxSonar-EZ provided a clear and reliable distance measurement in inches. We measured the reflection of a book at 6" and 12", and off a wooden board, a metal box, and a person's head at 10", 30", 60", and 120"; all readings were reproducible within 1" across multiple trials, although we did find a proportional error of approximately -3%. This systematic error can easily be corrected for in the firmware, but a more precise reading and 0.25" or better precision at the shorter distances will be required to obtain accuracy levels within a few % during close-range tests such as central visual fields. A recent update of the firmware allows for precision down to 0.1".

IV. Implementation

The hardware contains seven sensors housed in a circular housing (4" x 1") as depicted in Fig. 4. The side facing the

monitor houses 4 light-to-frequency sensors, each having a direct relation, 3 of which (TAOS TSL238Ds) are used to measure pixel size with the other (TAOS TCS230) measuring chromaticity and gamma values. The side facing the patient houses the digital sensors that are used to measure background illumination (2 more TCS230s). These sensors all communicate with the embedded PIC processor both directly and via an FPGA. Additionally the distance sensor communicates with the PIC processor via a UART. The PIC and FPGA are housed in the frame as well. The embedded PIC processor physically communicates with the host PC via its universal serial bus (USB), which also powers the electronics and sensors. The PC issues commands to the PIC, which returns success or failure responses. The final product is shown if Fig. 5.

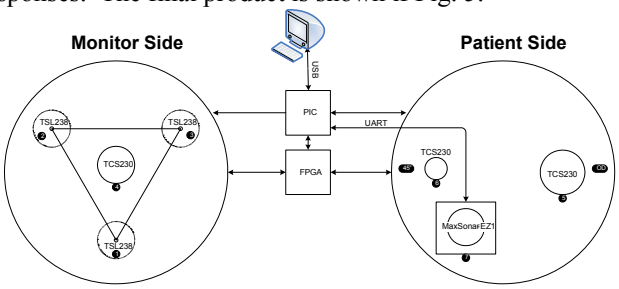

Fig. 4. System architecture for the PC Vision device. The monitor side determines monitor properties such as the pixel size and the refresh rate. The patient side determines the distance of the patient from the monitor as well as the ambient lighting conditions.

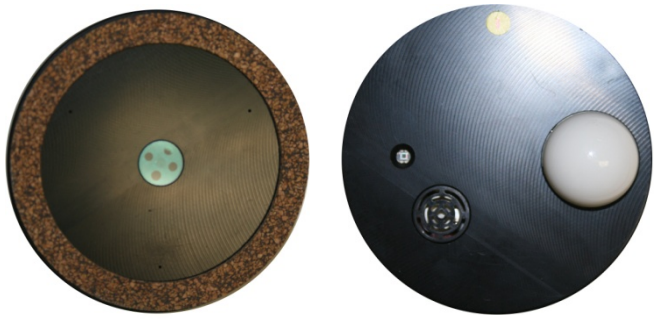

Fig. 5. Photos of the unit close up with the monitor side to the left and the patient side on the right. On the patient side, cork is used to rest flush with the screen and to avoid scratching. On the monitor side, the reflection of a directional light source is shown, highlighting a case where the glare sensor will indicate unfavorable ambient lighting conditions.

V. Operation

The device allows for feedback from application that is administering the vision test to the monitor and the lighting conditions in the room. An example of this is the condition where the luminance of the screen is checked under an initial diagnostic. The application sends out a request to the calibration system for a measurement regarding the luminance of the screen. The device takes that measurement and sends it back to the application. The application takes that information, compares it to the standard for that particular test, and adjusts the application's settings accordingly, e.g. if the screen is too bright, the application can darken the screen to compensate. An illustration of the use of the PC Vision device is displayed in Fig. 6.

VI. Conclusion

The results of these experiments show that several common screen calibration and test monitoring functions can be integrated into one unit performing all functions, even concurrently with vision testing. Which functions will prove most useful in practice is left open for a future study.

Fig. 6. Operation of the PC Calibration Device. The patient sits opposite the monitor as calibration tests are performed before and during the eye test ensuring the screen and illumination conditions meet a predefined standard (in this case a letter test is performed).

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