Application of cathode-ray tube technology to the clinical evaluation of visual functions

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Abstract. Cathode-ray tubes (CRTs) have many applications in the clinical evaluation of visual functions. They have been used to test visual acuity, contrast sensitivity, visual fields, and early development of vision in preverbal children. Because CRTs provide considerable flexibility for the definition of spatial and temporal components of the stimulus, their use provides an attractive solution to many visual stimulation problems. However, there are some limitations due to the scanning of the picture frame by the electron beam and also to the electron-photon conversion process. The spatial, photometric, spectral, and temporal characteristics of a specifically designed monochromatic television system are evaluated with reference to the physiological requirements of visual tests.

Subject terms: visual testing; cathode-ray tube; visual stimulation.

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1. INTRODUCTION

Systems for the examination of human visual functions that utilize cathode-ray tube (CRT) technology have been described for electrophysiological applications,[1-6] for testing visual acuity,[7,8] for evaluating visual fields,[9-13] for measuring contrast sensitivity,[14] and most recently for testing development of vision in preverbal children.[15] CRT technology presents many advantages for these applications because most of the physiological parameters, such as pattern shape, luminance, and contrast, can be put under microprocessor control. Furthermore, because CRTs are familiar to everybody, they are well accepted by patients.

In this paper, we describe a CRT system specifically designed for a quantitative evaluation of visual functions. Its photometric, spatial, spectral, and temporal characteristics result from engineering compromises and are presented with reference to the physiological requirements of visual tests.

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2. BACKGROUND

2.1. Physiological background

For any examination of visual functions, several parameters must be precisely defined:

The *ambient light level* determines the operating mode of the retina: rods are sensitive from 10^{-5} to 10^{-1} cd/m^2 (scotopic level), rods and cones operate simultaneously from 10^{-1} to 1 cd/m^2 (mesopic level), and cones are sensitive from 1 to 10^{+5} cd/m^2 (photopic level) (Fig. 1).

Contrast sensitivity is one of the major visual parameters. Contrast thresholds depend on the spatial and temporal modulation of the stimulus (Fig. 2). Contrast sensitivity varies as a function of the stimulus location in the visual field, of its wavelength, of its apparent angle area,[16] and of the light waveform.[17]

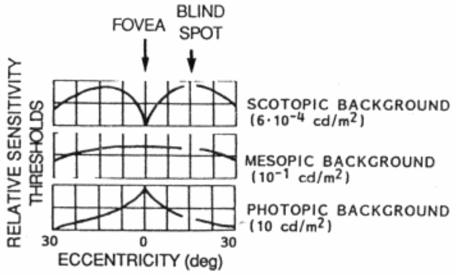

Fig. 1. Sensitivity threshold of the retina to a local stimulus projected over a uniform background as a function of stimulus eccentricity for three background luminance levels in the scotopic, mesopic, and photopic ranges. Relative sensitivity is expressed as 0.5 log unit per gradation.

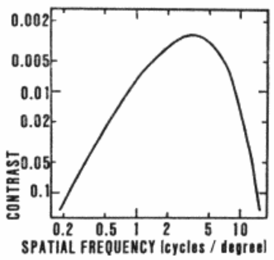

Fig. 2. Contrast sensitivity function.

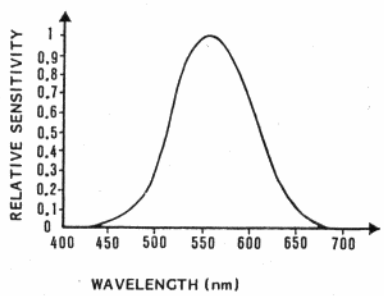

Fig. 3. Sensitivity of the light-adapted human eye (photometric curve).

The *light wavelengths* emitted by the stimulator determine which photoreceptor cells are activated. The wavelength sensitivity of the visual system ranges from 400 to 700 nm, with a maximum sensitivity at 555 nm in photopic conditions (Fig. 3).

2.2. CRT as an image generator

The physics of a CRT system is complex. Here, we summarize only the major features related to visual functions.

On a CRT system, a phosphor layer converts the electron beam energy into light energy. Phosphors are selected according to their light-emitting spectrum, conversion efficiency, and time response. For a given cathode temperature, the light intensity from the phosphor is determined by the cathode-grid voltage difference. Applying a modulated magnetic (or electric) field results in a deflection of the electronic beam and allows for the generation of an image by scanning over the entire CRT surface. The spatial and temporal features of the stimulus are defined by the scanning parameters and by the frequency and amplitude of the electron beam.

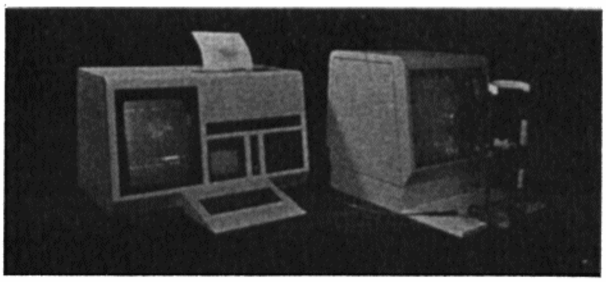

Fig. 4. Clinical setup of the instrument showing the CRT stimulator (right) and the computer (left).

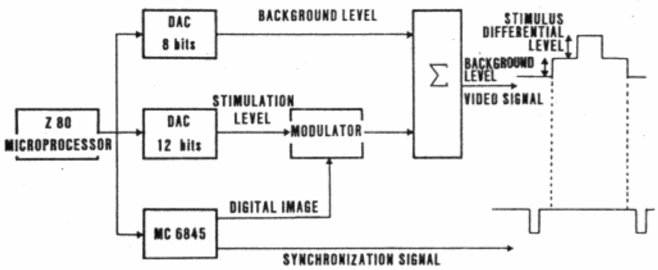

Fig. 5. Schematic of the electronic interface generating the video and synchronization signals.

3. DESCRIPTION OF THE CRT VISUAL STIMULATOR

Our visual stimulator is built from a standard, 20 in. diagonal, white P4 phosphor CRT (Philips RTC A50 120W) (Fig. 4). A graphic controller circuit (Motorola MC 6845) interfaced with a Zilog Z80 microprocessor generates a binary digital video signal by scanning a digital memory. Eight memory banks and the scanning starting address are selectable under software control, allowing the regeneration or translation of the entire screen at each new frame. An 8 bit digital-to-analog converter (DAC) defines the background level. A 12 bit DAC generates the stimulation differential level, which is modulated by the binary digital video signal and added to the background level (Fig. 5). The resulting video and synchronization signals are sent to standard dc-coupled electronic amplifier circuitry, which generates the voltages applied to the electron gun and to the deviation coils.

4. SPATIAL CHARACTERISTICS

Implementing a wide range of visual tests on a CRT screen is difficult, owing to the extremely large operating range of the human visual system with respect to the CRT system performance. For instance, the spatial resolution of the central retina is better than 1 arc-minutes, and the complete visual field covers about 180°. Obviously, such a high resolution cannot be offered. Fortunately, the spatial resolution of the eye decreases rapidly from the center of the retina toward the periphery. It is worse than 10 arc-minutes at an eccentricity relative to the eye gaze direction of about 10°. A compromise was found by implementing two different operating modes on the CRT screen (Fig. 6).

In the low resolution mode, the eye is 33 cm from the screen. The resolution is only 18 arc-minutes, but the visual field covered by the screen extends to ±30° horizontally and

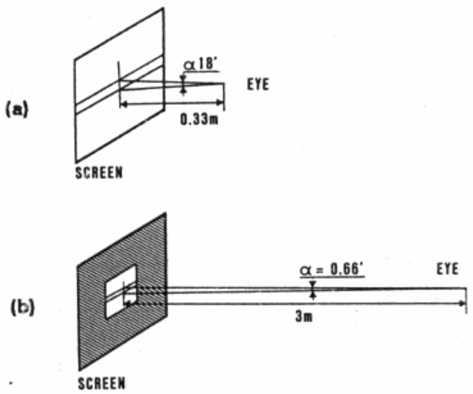

Fig. 6. Spatial characteristics of the stimulator in (a) the low resolution mode and (b) the high resolution mode.

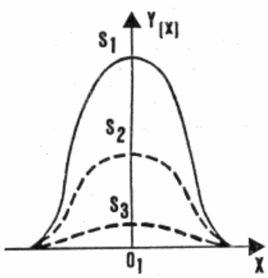

Fig. 7. Light distribution in a television spot for increasing electron beam intensities (S_1, S_2, S_3).

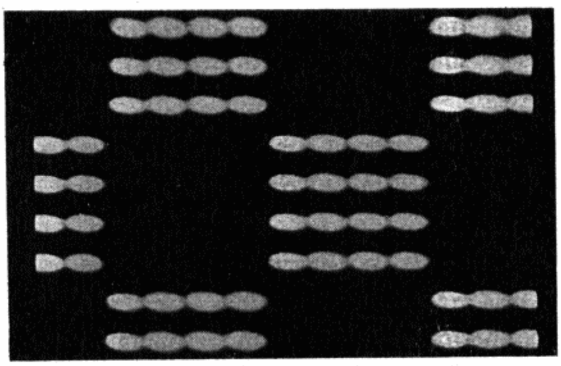

Fig. 8. Enlarged picture of part of the CRT screen.

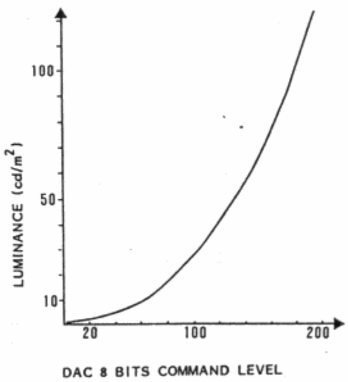

Fig. 9. Relationship between the background DAC input value and the ambient luminance on the screen.

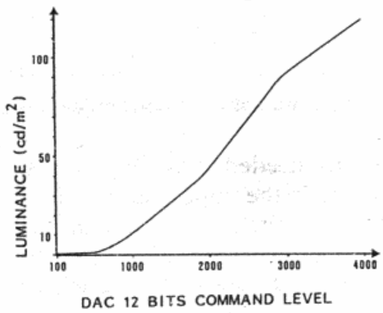

Fig. 10. Relationship between stimulus DAC input value and stimulus luminance. Background level = 10 cd/m².

±24° vertically, which is suitable for central and pericentral visual field examination. In the high resolution mode, a specially designed electronic circuitry allows for a reduction of the screen scanning area, which is divided by 9. With an eye-screen distance of 3 m, the visual field under test is reduced to 2.2° horizontally and 1.8° vertically. The resolution reaches 0.66 arc-minutes, which is suitable for visual acuity measurements.

Another problem with CRTs is the edge quality of the image. The light distribution resulting from a well-focused electron beam appears as a Gaussian distribution (Fig. 7).

Figure 8 is a photograph of a checkerboard pattern displayed on the screen, showing the effect of limited spatial resolution and contour sharpness.

5. PHOTOMETRIC CHARACTERISTICS

5.1. Relationship between the luminance and the command signal

Most measures of visual system performance are sensitive to the luminance and contrast of the stimulus.[8,18] For this reason, the relationship between the microcomputer digital commands and the luminance of the screen were investigated.

All photometric measures were performed with a Spectra Pritchard model 1980A-PL photometer with the following settings: distance from screen to photometer = 1.5 m, photopic filter, measurement area = 1° located at the center of the screen.

The dynamics of the electronic-CRT system are limited to 24 dB for the background luminance, owing to the 8 bit resolution of the DAC. This operating range is considerably less than the 100 dB range of the human visual system. In the low resolution mode, it was set to the 0.5 to 120 cd/m² bracket, which covers the high mesopic and low photopic levels used in most visual examinations. In the high resolution mode, the light output reaches 200 cd/m².

Figure 9 presents the relationship between the background DAC input and the ambient luminance (background luminance) obtained on the screen. Figure 10 is the curve for stimulation differential luminance (stimulus luminance). In both cases the relationship between the digital command and the luminance response is nonlinear. Furthermore, it is not stationary, owing to variations of the optoelectronic component characteristics. Calibration of this relationship is therefore a basic requirement when precisely controlled

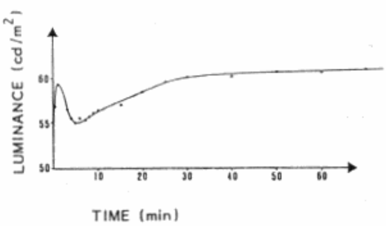

Fig. 11. Luminance stabilization in time after the power is turned on.

Fig. 12. Background light distribution over the screen.

luminance levels are needed. For this purpose, a photoelectric sensor is located in the upper part of the screen, allowing for background and stimulus luminance response calibration at the beginning of each examination session.

A warm-up delay and a stabilization delay are also needed when the CRT system is turned on or when its operating parameters are changed. Figure 11 shows the variations of luminance measured during the warm-up period. A minimum delay of 10 min is needed to obtain luminance stabilization within 10%. This calibration system allows for a control of the background and stimulus luminances within ±10%.

5.2. Luminance uniformity

In visual field examinations, both background and stimulus luminances should be controlled over the entire CRT screen to avoid local variations of retina adaptation and to maintain a uniform contrast ratio. The contrast ratio C is defined as

$$C = \frac{L_{stim}}{L_{back}} , \tag{1}$$

where L_{stim} is the stimulation differential luminance and L_{back} is the background luminance. The relative variation of the contrast ratio is

$$\frac{dC}{C} = \frac{dL_{stim}}{L_{stim}} + \frac{dL_{back}}{L_{back}} . \tag{2}$$

The contrast ratio threshold of normal subjects presents fluctuations of ±20%. To obtain such precision, both background and stimulus luminance levels should be controlled within ±10%. Figure 12 shows the background light distribution measured over the screen for a background luminance of 10 cd/m² in low resolution mode. The variation of the background luminance is ±10% for an eccentricity less than 25°. The stimulus luminance varies in a similar manner. Consequently, the contrast ratio fluctuation (Fig. 13) is only ±10%.

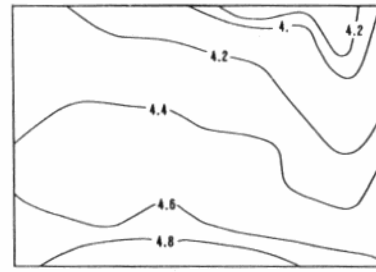

Fig. 13. Contrast ratio distribution over the screen.

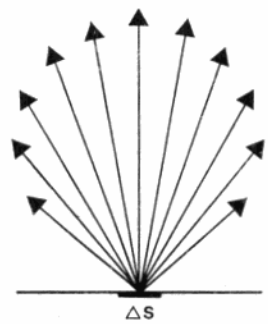

Fig. 14. Lambertian emission for a local element ΔS of the screen (luminance as a function of direction).

For short viewing distances, the convex curvature of the screen results in a decrease of luminance at the periphery due to nonuniform Lambertian emission of the screen (Fig. 14).

Another problem is the limited size of the screen background illumination compared to the visual field. When the examination is performed in a dark room, a strong afterimage effect is observed under photopic screen illumination. This problem is solved by using a room ambient illumination located behind the television stimulator so as to avoid parasite reflections of the source over the screen front plate.

6. SPECTRAL CHARACTERISTICS

The emission spectrum was studied with a Pritchard spectrometer (spectral analysis width = 5 nm, measurement field = 20 arc-minutes). The energy spectrum (Fig. 15) presents a principal response at 455 nm (blue radiation) and a secondary response at 560 nm (yellow radiation). These results are not affected by luminance level and emission direction. The same results plotted in the photometric domain (Fig. 16) show that the yellow radiation peak is coincident with the maximum of eye sensitivity. A slight blue dominance and the absence of radiation beyond 650 nm are also noticed.

7. TEMPORAL CHARACTERISTICS

Several factors influence the temporal characteristics of stimuli on the CRT screen: the electron beam scanning rate, the phosphor time response, and the high voltage power time constant.

A 100 Hz scanning rate is chosen for two purposes. First, it eliminates the flicker phenomenon, which is an important consideration in visual field examinations since the sensitiv-

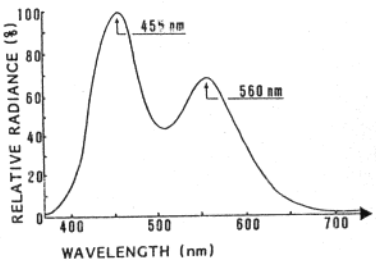

Fig. 15. Energy spectrum of the phosphor.

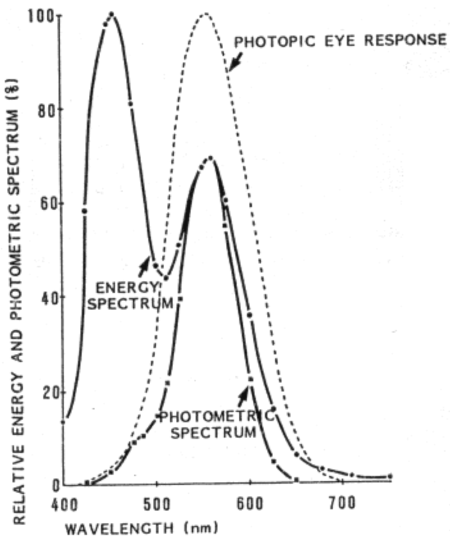

Fig. 16. Photometric spectrum: product of the phosphor emission curve and the eye photopic sensitivity curve.

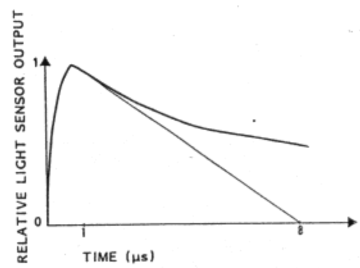

Fig. 17. Phosphor P4 response time.

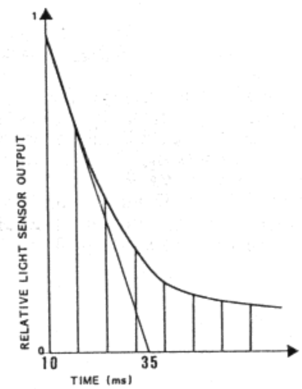

Fig. 18. Response time of the screen for flash stimulations (with 30 Hz stimulation).

ity of the visual system to flicker increases at the periphery.[19] Second, it reduces the time delay between the appearance of a stimulus in the upper part and the lower part of the screen. This delay must be taken into account in electrophysiological examinations: the fluctuations of the latency of the visual-pattern-evoked responses have been shown to be more important with a standard TV raster scan (20 ms) than with a mechanical system (10 ms).[20]

A phototransistor (Texas Instruments TIL81), set as a photodiode, was used to measure the phosphor time response from a screen area, 6 mm in diameter, which is scanned horizontally within 370 ns.

The time constant measured for the P4 phosphor is less than 8 μs (Fig. 17). Therefore, the local luminance of each screen dot appears as a pulse of light of short duration repeated every 10 ms. The effects of this phenomenon are still unknown.[21] However, a short persistence is needed for the generation of rapidly changing stimuli, such as flashes of light or motion pictures.

Generating images of high luminance requires a high electronic current that can exceed the high voltage power supply capability. The luminance response of the screen was measured for a high luminance flash stimulation (seven frames "ON" and seven frames "OFF") (Fig. 18), indicating a power supply time constant of 35 ms.

8. CONCLUSION

The goal of our study was to find the best compromise among the physiological requirements of the visual tests, the CRT technical characteristics, and economic constraints. Specific features that are not available on reasonably priced standard video equipment have been implemented: a precise control of background luminance and contrast, a high frequency scanning rate, and the capability of generating rapidly moving or alternating stimuli. This CRT stimulator is currently used in several clinical setups for testing central and pericentral static visual fields, visual acuity, contrast sensitivity, visual development in preverbal children, and visually elicited electrophysiological responses (visually evoked potentials and electroretinograms).

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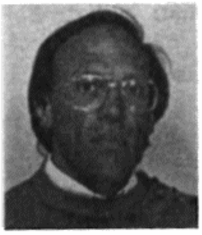

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Duc Dung Nguyen was born in Vietnam in 1951. He received an electronic engineering degree from the Ecole Universitaire d'Ingénieurs de Lille, France, in 1977 and the doctor of engineering degree from the University of Lille 1 in 1980. He is currently a research worker of the Institut National de la Santé et de la Recherche Médicale (INSERM), France. His research interests include the study of the development of visual functions in newborns.