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What characteristics a clinical CSF system has to have?

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We discuss the characteristics a system to measure the contrast sensitivity function (CSF) in the ophthalmologic clinic has to have. We propose that this system should be computer based in order to assure flexibility and precision. Besides the original calibration, this equipment needs an auxiliary system to keep the working conditions allowing periodical gamma corrections. We try a calibration method based on visual comparisons and show that it is valid and simple. We propose to use an adaptive psychophysical method to obtain contrast thresholds that assure a good compromise between precision and duration of the whole test. Finally, we propose that the system has to have its own normality curves for the different age ranges allowing the practitioner to perform clinical evaluations. Summing up, we can say that taking into account the above issues, the fidelity of the stimuli will be guaranteed and the challenges entailed in its transference to the clinic will be overcome.

Keywords: contrast sensitivity, ophthalmologic clinic, standards.

1. Introduction

Human spatial vision has the ability to detect and process stimuli of varying size and contrast; this ability can be evaluated through contrast sensitivity function (CSF). This function is obtained from the threshold contrasts that the visual system requires to detect or to discriminate a sinusoidal stimulus of any spatial frequency (the inverse of a grating period). The inverse of the threshold contrast is the contrast sensitivity (CS). A complete CSF curve results from the threshold contrast measurement for the entire range of spatial frequencies to which the system is sensitive.

The clinic utility of CSF is determined because this function gives information about the optic part as well as the neuronal part of the visual system, thus allowing the ophthalmologists to attain an evaluation of functional vision [1]. From the clinical standpoint, the CSF test can detect vision loss and can give way to get a better diagnosis

of early-stage diseases [2], such as early retina and optic nerve problems, in which visual acuity does not present alterations in its first stages [3]. In this way, CSF provides information not only about the ability to detect objects in a vast range of situations [4], but also to detect anomalies [5, 6].

There has been a renewed interest in CSF for clinical use [7, 8]. Studies show that it can be a helpful tool to be part of a functional visual assessment, especially when a more thorough evaluation is necessary other than the one given by Visual Acuity [9–11]. It is being used successfully as an aid in making decisions about cataract surgery [12]. It has likewise shown to be effective in the diagnosis of glaucoma [13–16], optic neuritis and multiple sclerosis [17, 18], and in the following up of visual performance changes after refractive surgeries [19–23]. It can also help assess visual performance in the elderly [5, 24–27] or in people with low vision [28, 29]. Studies on patients with congenital nistagmus have also shown the usefulness of CSF [30].

Moreover, it is considered advisable to incorporate these kinds of visual tests to determine a person's eligibility to drive [31]. This is even more so considering that elderly people – whose population percentage is on the rise – undergo an ageing process of their visual capacities [32, 33] and are more sensitive to factors such as glare, all of which are aggravated by the use of glasses when compared to the use of contact lenses [34].

There are several commercial tests, some of them are based on printed or translucent cards and they use letters [35–37] or sinusoidal gratings [2, 38, 39]. The printed cards specify the illuminance levels that must be measured on them in order to achieve measurement (FACT, for instance), or they are loaded onto a system that ensures the fulfilment of these conditions (CST Digital). The translucent ones incorporate the lighting system from behind (CSV-1000). Research shows that the contrast sensitivity curve provided by sine-wave grating tests is more sensitive and informative than the results obtained from low-contrast letter acuity systems [2]. Tests based on printed cards have a limited ability to discriminate the subject's answer since the stimuli have a fixed number of contrast values [40]; the result obtained is only one because the process of determination is carried out only once; the control of illumination is not always easy to get; and reference ranges are not discriminated by age.

As a counterpart to the possibilities mentioned, there is computer-based equipment that has sophisticated and expensive graphic cards as the VSG (Cambridge Research Systems). There are also other systems that need libraries for visual stimuli generation, such as the VideoToolbox and the PsychophysicsToolbox, both of which require expensive software (a C compiler or MatLab, respectively). These alternatives have neither the facilities needed to be adapted to clinical measurement nor the elements to carry out diagnostic tests because they are oriented towards the research on visual sciences. However, even though the usefulness of this CS function in clinic is well known and there exist a variety of commercial systems, its use has not extended so much in the ophthalmology.

Our goal was to evaluate different methods and technologies available at present to propose the main characteristics a CSF system has to have to be useful in the clinical

practice, in order to achieve reliability, accuracy and flexibility. For this purpose we were checking each one with our own system developed. First of all the system has to be computer based and to have an easy procedure to periodically calibrate it. Besides, it is necessary to select a psychophysical method to determine the CSF and to incorporate ranges by age to compare the measurements from the patients.

2. Hardware components and calibration aspects

The development of a CSF system implies having equipment capable of presenting low contrast sinusoidal gratings in the entire range that the visual system is sensitive to. The use of a system based on a PC is the more appropriate alternative to get the grey scale resolution guaranteeing the fidelity of the stimuli. The minimum requirements of the PC are a Pentium processor, 512 MB of RAM and a graphic card that allows two video cards (an AGP port in our case) to be controlled.

2.1. Display selection

The display should be able to reproduce the attributes of an image with such a precision that the separation of the responses from the normal conditions could be attributed to visual problems. Nevertheless, issues such as size cost and power consumption are factors that should not go unwatched once the main objective has been achieved. It was necessary to choose a given technology from among the three existing ones on the market. At present, plasma displays are not considered a valid choice since they do not have the versatility required in ophthalmology and they are highly expensive. In order to decide between LCD (liquid crystal display) or CRT (cathode rays tube) displays we compared the most important parameters for reproducing sinusoidal stimuli of very small and highly controlled contrast:

1. Dynamic range (DR) of luminance: generally, LCD screens have greater maximum luminance than CRTs, however, minimum luminance is also higher, which leads to greater contrast proportions for CRTs.

2. Gray level resolution: rather than the absolute value of this number, what is important is the relationship between luminance and DAC voltage. While CRT presents an area of greater saturation towards high values of DAC voltage, LCD screens tend to show a flat area not only at high digital levels but also at low levels. In this sense, the advantage of working with CRT is remarkable.

This means that nowadays only CRT monitors have DR characteristics and gray level resolution which make it possible to show low contrast sinusoidal gratings. However, in terms of size, LCD is at an advantage of CRT monitors, but also this advantage is compensated by the price of CRTs. Another disadvantage of LCD screens is that emerging light is not homogeneous in all space directions, as is the case of CRT, although this deficiency is not very important because the task is foveal. We know that in a near future the CRT screens will replace the selected CRT ones.

Two monitors of the same brand were compared, one LCD and the other CRT. They bore similar dimensions, pixel size, and response time and rest consumption.

Although maximum luminance in LCD was slightly more than double, contrast proportion for CRT is 6 times higher; horizontal and vertical vision angles are slightly higher in CRTs, as well as maximum resolution and colours borne. In the end, a 19" CRT display was chosen, with a screen size of 35.2 cm × 26.4 cm (Samsung SyncMaster 955 DF). The video card resolution was set at 1600 × 1200 pixels with 32 bits for colour representation. A monitor of 15" or 17" can be used if no spatial 2AFC paradigm is implemented.

2.2. Gray level resolution of the system

The gray scale resolution of the standard VGA video card is insufficient to reproduce the lowest contrast and by this reason it is necessary to consider auxiliary tools. In order to expand it we incline toward the option of a video attenuator [41] and a module for the adaptation of the monitor to the video signal. Both auxiliary systems enable the color resolution of the monitor jumps from the 8-bit to more than 13 bits.

The video attenuator integrates the output signals r, g and b of the graphic card into one unique output by means of a passive network that assigns each input signal with a different attenuation level. This implementation was originally designed to be used with achromatic monitors due to the only output attenuator; meanwhile, the authors proposed the use of two graphic cards for colour monitors with an attenuator that integrates channels r, g and b of both [41]. Instead of this solution, in our system, we connect the monochromatic attenuator to the three joint inputs of the colour monitor and modify their input impedance so as to adapt it to the output impedance (75 ohms) of the monochromatic attenuator.

The beat-stealing algorithm [42] instead of a video attenuator could be considered but it allows around 10.8 bits, an insufficient number of gray levels to achieve a precise reproduction of a sinusoidal stimulus of as lower a contrast as 0.2% used in the measurement of the greatest sensitivities. Besides, the beat-stealing technique requires accurate information about the effect of the radiant energy on the human eye, which could vary substantially for individual observers reducing the accuracy of the process.

2.3. Calibration

The system has to have an original (or initial) careful process of calibration to correct the different nonlinearities in the video-monitor card system and so asserting the fidelity of the stimuli (for a revision, see [43]).

The gamma correction parameters should be determined by means of a photometric procedure measuring the absolute luminance with a luminance meter and computing the parameters k and γ of the relation between the luminance and the DAC voltage:

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

However, the user needs update this calibration by a periodical procedure. One alternative is by means of a psychophysical method based on visual comparison [44]

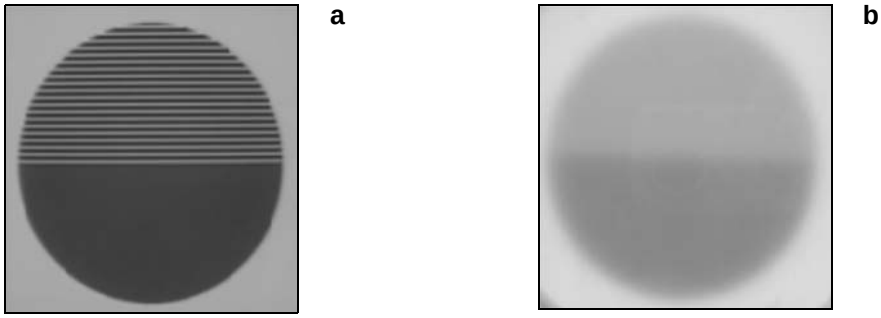

Fig. 1. The bipartite field used to perform the brightness match task in the visual calibration process: without diffuser (**a**), with diffuser (**b**).

which does not require a luminance meter. In this work, we show that this method could be successfully implemented on a standard PC. We checked it as follows: a 400-pixel diameter circle is presented on the screen, in one of its halves (A), the maximum DAC signal is applied (a value of 255) to a previously established pixel fraction; and in the other semi-circle (B), the signal applied has a varying value of 0 and 255 on all pixels, thus achieving a given luminance level (Fig. 1). This signal is controlled by the subject that calibrates the equipment, and his task consists in varying the luminance in B until it matches the brightness of half A (brightness matching task). These matching values give the levels of voltage in B associated to the luminance value in A, that is, in the proportion of lit pixels. Once the process for pixels lit for ten different rates is over we fit the data to obtain the parameters γ and k. Due to the fact that the different luminance percentages generated in the upper field present a striped pattern that makes the matching task difficult, a diffuser glass was necessary to be introduced in the system that covers both fields of the stimulus, which facilitates the subject's task.

In order to evaluate the reliability of the visual calibration we compare it with a photometric one in the equipment proposed. The experiment was carried out with 7 observers, each of whom repeated the test 4 times. Among the observers, some had no experience in this kind of psychophysical determination, while others did. There is high repeatability in each observer and among observers, as shown in Figs. 2**a** and 2**b**, respectively. The values obtained were $\gamma = 1.72 \pm 0.04$ and $k = 0.98 \pm 0.01$, for the visual calibration, while photometric calibration had the values of $\gamma = 1.733 \pm 0.004$ and $k = 0.992 \pm 0.001$. The conclusion is that the parameters are the same within experimental errors, thus validating the visual calibration technique. The results indicate reliability of the method, a reduced measuring time of approximately 10 minutes and ease of performance, all the features being sought by the practitioners.

Another aspect of the monitor behaviour to be taken into account by an initial calibration is the MTF of the display. In spite of the MTF being determined only for vertical gratings because of the interaction between neighbouring pixels provoking a contrast decreasing [45], the MTF of the display in the direction of the luminance

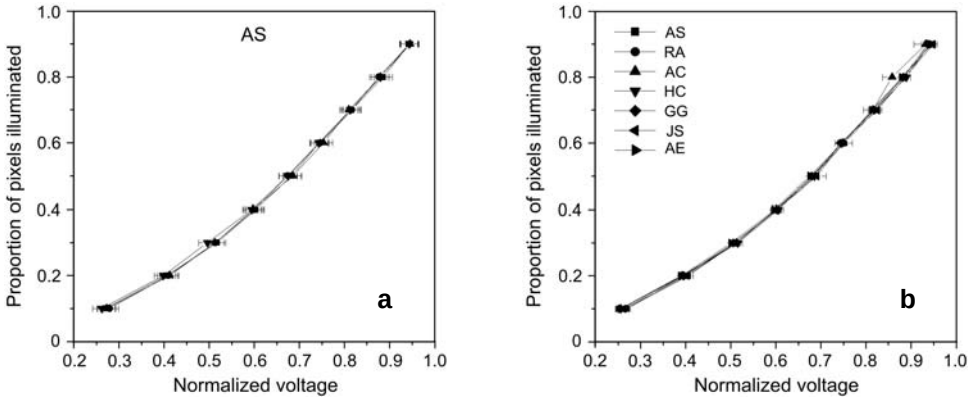

Fig. 2. Luminance *vs.* voltage: data obtained for subject AS (**a**), data for the seven intervenient subjects in the experiment, each point is the mean of four measurements (**b**).

variation of our quasi horizontal gratings has to be determined [46] since we also found in this case contrast reduction. We measured the maximal and minimal luminance of gratings and then computed the effective contrast in the screen. This measurement was done for all the spatial frequencies used in the system (characterized in pixels per cycle) and for seven low contrasts in the same range used for the determination of contrast sensitivity. To this end, we used an LMT 1009 luminance meter with approximation lenses that allows measuring a single pixel. The results are plotted in Fig. 3 showing the slopes of the lines to be fitted to the data decreasing as the spatial frequency grows. These slopes are plotted as a function of spatial frequency in Fig. 4 and represent

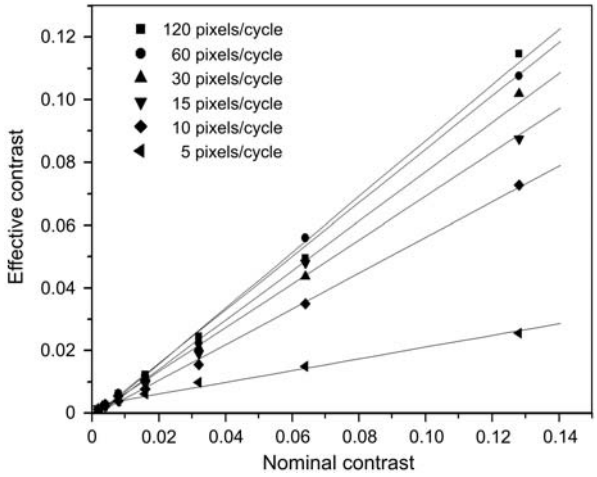

Fig. 3. Contrast measured in grating counterclockwise direction (+7°) as a function of nominal contrast for seven spatial frequencies characterized by the number of pixels per cycle. The lines represent linear fits that show the different slopes obtained for each spatial frequency.

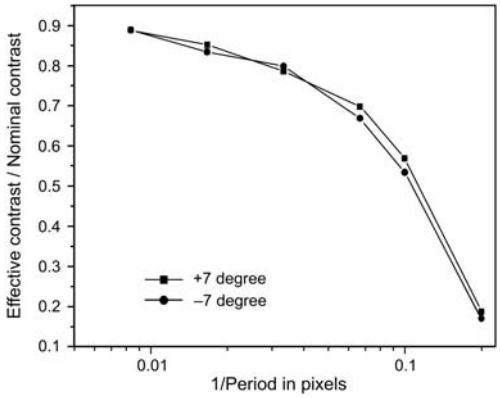

Fig. 4. Modulation transfer functions obtained for stimuli of both orientations. In the abscissa axis, the spatial frequency is represented as the inverse of the number of pixels.

the MTF of the display. From the operative point of view, when sinusoidal gratings are generated, compensation has to be introduced incrementing the nominal contrast by a coefficient in inverse proportion to the modulation factor for the corresponding spatial frequency.

Both gamma correction and the monitor's MTF measurement have to be carried out taking into account the fact that the stimuli appear in the central area of the monitor, thus avoiding misconvergence in the peripheral area that translates onto the image as an unwanted blur. On the other hand, calibration stimuli have to be small enough to assure that the mean luminance drives the value of the display current supply approximately constant; this mean luminance has to be the same when taking measurements as when performing some calibration. In this way, the calibration parameters are guaranteed to be valid in the measuring process.

3. CSF measurement: software, methodology and experimental set-up

Special purpose software for measuring CSF has to be developed. The choice of methodology is crucial for providing a transferable system for the clinic. Once the stimulus fidelity is assured and good precision in visual function determination is achieved, the measurement should be done in relatively short periods of time.

3.1. Stimuli

We propose static sinusoidal gratings to be used as stimuli [2]; they were slanted 7° in relation to the horizontal one, both clockwise and counterclockwise (Fig. 1), maintaining the same response property, since both orientations belong to a unique orientation column in the striate cortex [47]. The presentation time for each stimulus in its nominal contrast could be around 500 ms. Times below this value produce

an insufficient detection of the pattern while longer times unnecessarily extend the measurement [48], the visual size has to be slightly greater than the foveal size – around 6° or 7° is good enough. The spatial frequency values used have to cover the low, medium and high ranges of spatial frequencies [32, 33, 39, 49] – from 1 to 24 c/deg.

The maximum luminance of a CRT monitor is approximately 150 cd/m^2. The grating mean luminance should be nearly in the middle of the monitor range of luminance as well as the immediate surrounding luminance, which is not a relevant variable [50, 51]. Although the normal room lighting conditions do not change the visual performance [52], a dark surrounding would be better to avoid distractions. For that reason, the subject should be advised to look at the display every time.

3.2. Distance of vision

From an optometric point of view, it is convenient to perform the measurement as far away as possible from the visualization device [53] so as to minimize the demand for accommodation/convergence, taking for granted a person who is normal or corrected ametropic. Considering limitation of space a compromising solution could be a distance of 1.5 m, which considerably lowers the demands.

3.3. The method and the task

We propose an adaptive method because it has the advantage of shortening measurement times significantly, controlling precision. In this way, we have used the QUEST [54] adaptive method whose algorithm makes a Bayesian inference of each response the observer gives, and hence the following contrast to be presented is established. The observer's task consists in discerning between the two possible

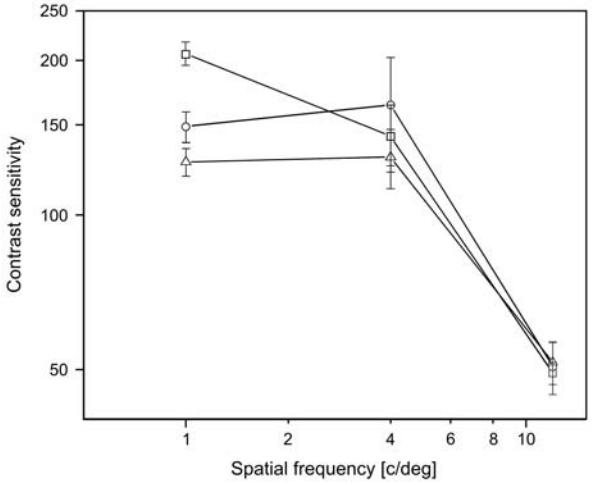

Fig. 5. Contrast sensitivity obtained for 20, 30 and 40 trials with spatial frequencies of 1, 4 and 12 c/deg. Each point is the mean of 5 measurements and the bars represents a standard deviation.

positions, thus being forced to pick one of them – even if he could no longer see the stimulus – by pressing the appropriate button.

According to a simple experiment we determined the number of trails needed to obtain a good estimation of the threshold. We have carried out measurements considering 20, 30 and 40 trials with spatial frequencies of 1, 4 and 12 c/deg in naïve and experimented subjects. In Fig. 5, the data obtained for one observer (32 years old) are plotted. For frequencies of 4 and 12 c/deg, there are no differences among the number of trials, instead for 1 c/deg, there can be seen differences between measurements with 20 trials and those performed with 30 and 40 trials. These observations were confirmed by means of an ANOVA with $p < 0.05$ for 1 c/deg and $p > 0.05$ for 4 and 12 c/deg. Moreover, if we compare the set of data collected for each number of trials there are no differences between 30 and 40 trials ($p > 0.05$) although it is not the case if we consider 20 and 30 trials ($p < 0.05$). From these results it was possible to establish that for 20 trials, there can be an overestimation of the threshold, while with 30 or 40 measurements, equivalent results were obtained. However, because time is a very important factor – as in clinics – the option to go with was the one with 30 trials.

4. Reference curves by age range

Finally, probably one of the most important characteristics, is that a CSF clinical system has to incorporate normality ranges according to age. In this way, the system gets sensitivity for the diagnosis and follow-ups of visual pathologies. The methodology used to determine the normal curves must be the same as the one suggested for the measurement in clinics.

We have determined reference curves with 55 subjects, 11 per age range (20–29, 30–39, 40–49, 50–59, 60–69 years old), all of whom agreed to an ophthalmologic check-up designed according to APA (American Psychological Association) regulations for the work performed on human beings, and to international norms on bioethics and the ones stated in the Helsinki Declaration. Since the goal is to establish curves that will help detect vision anomalies, a visual acuity unit (AV = 1) was required. The latter would be corrected in situ by an ophthalmologist for the distance of the test during measurement sessions; an exam of the ocular means (cornea and crystalline biomicroscopy) and the fondus, as well as an adequate control of intraocular pressure (contact tonometry). The group of people included in the measurement was free from ocular pathologies, though some needed refractive correction. Each observer did two series of measurements with each eye: the first was deemed part of the learning process and only the data from the second round were considered. Measurement time for the six spatial frequencies in each eye was approximately 10 minutes, four times less than when using a constant stimuli method, which certifies the efficiency of clinical measurements based on adaptive methods.

Of the 5 curves obtained, and according to the standard mean error – which indicates the degree of precision estimated in the "centre" of the distribution of

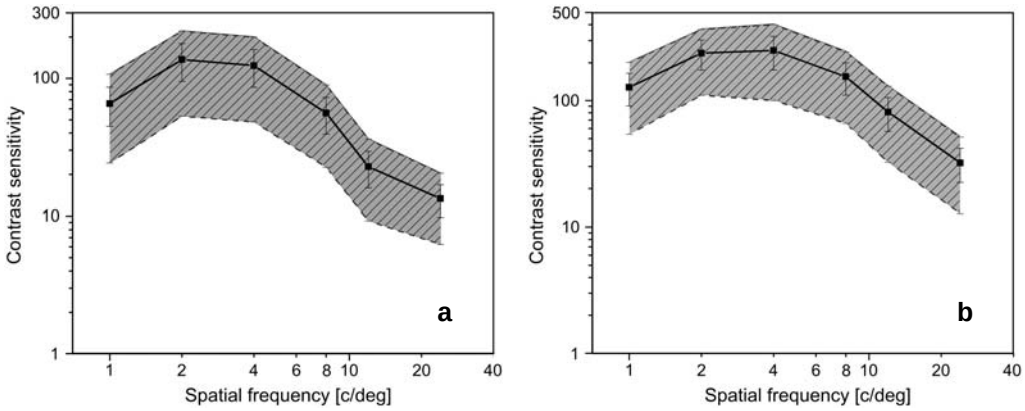

Fig. 6. Normality interval for the age ranges of 20 to 49 (**a**) and 50 to 69 (**b**) years. Each point represents the mean of the sample, vertical bars indicate a standard deviation and the shadowed area represents the two standard deviations.

means – a separation of the curves in the age ranges 20–49 and 50–69 years old is noticed. In clinical practice, it is common to set normality intervals according to the following criterion [55, 56]

$$\text{Normality interval} = \mu \pm 2\sigma \tag{2}$$

where μ is the mean for the distribution of means and σ is the standard deviation. This implies that, if we measure a new subject, there is a 95.45% probability that his sensitivity curve will drop within that strip. Applying such criterion, we obtain graphs illustrated in Fig. 6**a** for the 20–49 age range and in Fig. 6**b** for the 50–69 age range.

Considering our results and those from the quoted papers we think that these two ranges of normality are enough for the system to get a good ability to discriminate a separation from normality. In addition, the equipment should have the alternative to visualize the course of the measurement through another monitor and the possibility of showing the results obtained and to contrast them with the reference strips as well as to print a report with test results.

5. Discussion

The present challenge in the CSF clinical measurement is to be able to count on reliable equipment with an appropriate measuring methodology, taking into consideration two basic requisites. The first one is for the results obtained to have enough accuracy and reliability. The second one is for the time taken in measuring not to extend too much.

Our decision of choosing a computer based system is in good agreement with earlier works. For instance, RUBIN [57] showed more reliability on CS measurements done with CRT-based equipment with respect to printed-card tests through a test-retest

analysis, and other works have shown the sensitivity of electronic equipment-based tests for discriminating the normal case from the pathological one [13, 58].

In relation to the methodology we propose an adaptive method because its superiority as regards the times involved is well known. Although some authors [59] had already noticed the inefficiency of the constant stimuli method for some applications, it has continued to be widely used due to its simplicity for experimental implementation. Our results showed that an adaptive method like QUEST allows more reliable results than those attained with constant stimuli and in notably less time consuming. Furthermore, while the QUEST method immediately estimated threshold contrast, the constant stimuli method requires further processing, consisting in fitting the data into some mathematical model that describes the psychometric function from which the threshold contrast can be obtained.

Furthermore, the clinical measurements will be performed in less time than those obtained when all the spatial frequencies are presented, which is about 10 minutes. For instance, evaluating a smaller number of spatial frequencies since the practitioner will not always need information on the entire range. CS measurement in each spatial frequency takes approximately one and a half minute, which means that in order to determine the threshold contrast for just 2 spatial frequencies the practitioner needs only 3 minutes.

On the other hand, the adaptive method-based measurement could be quicker if the estimated CS value were basically within the area of normality. In this case, the trial sequence can be interrupted thus reducing measurement time to less than one minute, since less precision is required. The same criterion may be considered when encountering the system with CS estimates which are much lower than normal. Only in those cases where CS estimation is near the inferior limit of the area of normality will the system demand a greater number of trials which will take up more time to allow a more precise determination in order to adequately discern the normal case from the pathological one.

6. Conclusions

We have established the characteristics a CSF system has to have to be used in the ophthalmologic clinic. First of all we discuss how to generate very low contrast sinusoidal gratings with high accuracy. Then we propose that for the practitioner to be able to realize a clinical evaluation of CSF measurement, the system has to have normality curves for different age ranges. At the same time, we demonstrate that a PC to which components and calibration procedures are added in order to use it as a measuring tool, allowed the presentation of grating with contrast lower than 0.2% in establishing threshold contrasts. Apart from using a monitor to present sinusoidal gratings, the illumination level to which the patient's visual system adapts itself is determined by monitor parameters and by the luminance intended by the equipment operator taking the measurements. Another important advantage is the incorporation

of a module of visual calibration, allowing it to keep the working conditions independent of a photometer. Finally, we suggest that this kind of system has to have at least two ranges by age.

All these characteristics are necessary if the equipment has to be used in clinic, because: *i*) measurement can be repeated as often as necessary because the stimuli are presented randomly, *ii*) it can be periodically calibrated, *iii*) the adaptation luminance is set mainly by monitor luminance, which makes the system very strong for complex environments, *iv*) measurements can be compared with normal ones according to age of each patient.

In this way, a computerized system for contrast sensitivity tests with characteristics mentioned in this paper can be used in the clinic as well as in research laboratories, in driving permit controls and in screening of population like that of school-age children.

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