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A statistical criterion to establish normal ranges for age in a contrast sensitivity function test

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In a previous work (Opt. Appl. **39**(2), 2009, pp. 415–428) we established the characteristics that a computer-based contrast sensitivity function (CSF) measurement system has to be used in the opthalmological clinic. In order to obtain a generalized use of CSF in clinics and as a screening tool, the necessity to incorporate a normality range by age was also suggested. It will also be important to establish how many reference curves are necessary, because in the last decades, different ranges have been presented in the literature. In the present work, our purpose was to show how to distribute the observers in terms of the statistical variations of CSF as a function of age in a normal population of healthy eyes. We then evaluated the utility of these curves in the detection of vision problems and, finally, the possibility of using them as a screening tool considering a reduced number of spatial frequencies. We used a computer-based CSF measurement system to present sinusoidal gratings whose values range from 1 to 24 cycles per degree. Three different groups (control, clinical and non-clinical) of subjects were considered. From the statistical analysis we obtained two ranges of normality, based on significant differences that appear around the age of 50. As we were interested in evaluating if this separation could increase the sensitivity of the test, we also performed a series of measurements in a clinical environment. As an interesting possibility of usage of a vision test is screening, we also measured people in conditions relatively different to those found in laboratories or clinics. We observed that this division into two ranges allows a better discrimination, especially for young adults. Measurements show an improvement of 22% in the detection of vision anomalies.

Keywords: contrast sensitivity, ophthalmological clinic, normality references.

1. Introduction

Throughout several decades the contrast sensitivity function (CSF) has been seen as a potential tool to evaluate people's spatial vision. It has the main advantage of being a non-invasive test which allows us to analyse the global behaviour of the visual system by means of stimuli that vary both in size and contrast ranges. This CSF test is a recommended part of a functional visual assessment [1–3], and its complementary role

with the wave-front aberrometry [4] and visual evoked potentials [5] has been highlighted. In fact, although the Snellen visual acuity is frequently considered as a "gold standard" in subjective evaluation, this measurement provides less realistic information due to the fact that it reflects only one of the necessary abilities that make up good sight: visualizing details with high contrast. Also, it has been pointed out that standard visual acuity normally underestimates the degree of vision loss suffered by older people when the viewing conditions are non-optimal [6].

In this sense, CSF has been shown to be a good indicative of visual performance in certain perceptual, everyday tasks [7], and other complex tasks that comprise strong visual components [8]. Different forms of eye diseases have been studied using CSF in a clinical setup (*e.g.*, cataracts [9], neuropathies such as glaucoma [10], macular degeneration [11], diabetic retinopathy [12], refractive issues [4], surgery [13], *etc.*), the effects of certain substances (such as alcohol [14, 15], solvents [16, 17] or mercury [18, 19]) or even neurological disorders [20, 21]. The amount of data collected using the CSF in these different areas and application fields show its relevance for vision research.

1.1. CSF test

Different tests and equipments have emerged for determining CSF. These can be divided into two main groups according to the support used: those based on charts (printed or translucent for back-lighting) and those based on electronic displays. In the case of electronic-based tests, they generally use sinusoidal gratings. However, as has been noted since the middle of the 90s [22, 23], CSF has not been definitely established in clinical practice, perhaps because of the great number of variables that affect its determination, among which are the measurement procedures and the equipment used. In fact, although some chart tests may look similar, several important differences exist between their contrast interval, task, illumination, size of target, *etc.*, showing significant differences when applied to the same sample [24].

Nowadays, with cheaper processing power, a computer-based test seems a good option [25], allowing the use of fast psychophysical procedures to obtain the contrast thresholds, giving the possibility of controlling other characteristics of the stimuli such as its temporal modulation. In this case, the quantity of stimuli has no other limit than that of the time desired to be invested in the test. As the computer could control the number of trials according to the subject's responses, a reduction in the bias per guessing is also achieved.

1.2. Ageing and normal curves

In order to obtain a generalized use of CSF in clinics and as a screening tool, it is necessary to incorporate a normality range. But one of the strongest restrictions when measuring the normal curves is that they have to be determined by the same equipment and the same psychophysical method with which the measurements will be carried out in the clinics. It will also be important to establish how many reference curves are necessary, because in the last decades, different ranges have been presented

in the contrast sensitivity literature. In these works, the observers were basically grouped in three ways.

1. One group was formed including people of very different ages, with intervals as wide as 5 to 94 years old [26]. In this category, we can place the work of GINSBURG *et al*. [27] which is probably the first that systematically measured a large number of normal observers using a computerized system and sinusoidal gratings. Sometimes the works were focused on assessing the quality of the different tests [28], but the wide ranges utilized could mask the differences among observers who have diverse visual characteristics.

2. Two distinguishable groups were set up with people whose ages were quite different [7, 29, 30]. This design was used with the intention of investigating the differences caused by age more than making age related norms. The number of people included in the group of older adults could be the same or higher than the number of people in the younger group, mainly due to the increase in individual differences caused by ageing [31].

3. Various groups were formed in which the ages were distributed into regular intervals covering a range that went from youths to older subjects (*e.g*. [18]). This was recurrently employed when the objective was to assess the changes in CSF related with the normal ageing process. A frequently observed option is to group the observers by decades [32, 33]. The number of subjects may be similar in all the groups [34] or increased according to age in order to compensate the greater variability of older observers [31, 35].

It is worth mentioning that for space reasons we have cited only some works of each type, just to exemplify the more common strategies that have been used in the literature to group the subjects.

1.3. Our work

It is well-known that there are a number of changes due to the normal ageing process which gradually affect the optical and neural parts of the visual system [36]. However, it was not clear if any of the considered works had separated the observers into ranges by using the information of age related variations, which would be relevant when defining normal curves for clinical applications. Therefore, our purpose is to show how to distribute the observers in terms of the statistical variations of CSF as a function of age in a normal population of healthy eyes. We then evaluate the utility of these curves in the detection of vision problems and, finally, the possibility of using them as screening tool considering a reduced number of spatial frequencies.

2. Methods

2.1. Apparatus

We used a computer-based CSF measurement system to present sinusoidal gratings. This system and its calibrations were described in detail in our previous work [25]. Briefly, it consists of a modified PC that serves as a generator of high quality mono-

chromatic visual stimuli. The maximum luminance was 150 cd/m^2 and the sinusoidal gratings were generated using a mean luminance of 70 cd/m^2. In all the conditions (vision laboratory, ophthalmic clinic and technology fair) the monitor surround was controlled to avoid potential reflections, glare or the influence of other possible distracting elements nearby.

2.2. Contrast sensitivity measurement

The protocol for this study was approved by the Ethical Committee of the National University of Tucumán, and followed the tenets of the Declaration of Helsinki and the American Psychological Association for work with human subjects. An Informed Consent was obtained from all the subjects.

CSF was measured using sinusoidal gratings of different spatial frequencies ranging from 1 to 24 cycles per degree. The time each stimulus was presented in its nominal contrast was 500 ms. Contrast was temporarily modulated with ascending and descending ramps of 250 ms and was also spatially modulated by a Gaussian function (generating a Gabor patch) in order to make the stimulus appear in a gradual manner. The observation distance from the monitor screen to the observers' eyes was 1.5 m. The visual size of the stimulus patch was 6.4°. A modified adaptive psychophysical method based on QUEST [37] algorithm was used to precisely determine the threshold. According to the responses, the algorithm determines the following stimulus and, after a mean of 30 presentations, it calculates the contrast sensitivity (the final number of presented stimuli depends on the quality of the subject's responses). The measurements began with lower spatial frequencies and ended with the highest ones. It was a discrimination task with a forced choice paradigm of one interval. By pressing a button, the observer had to indicate the stimulus inclination with respect to the horizontal (7° clockwise or 7° counter-clockwise). The stimuli were selected with the intention of using orientations deviated from those of maximum sensibility such as horizontal or vertical ones, which are already implemented in other commercial tests. The possible orientation bias of this kind of stimuli is reduced by refracting correctly the subject before starting the test. If the correct refraction is not achieved, it would be in addition to or masking other possible factors that may cause a contrast loss.

Once the subject was located in position, he/she was asked to stare at the monitor screen to achieve visual adaptation. Meanwhile, the experimenter instructed the observer about the way in which the measurements would be done, read the protocol which states what the stimuli are like, and explained to the subject the use of the response box. After this, there was a brief practice period to familiarize the observer with the test. All the measurements referred in this work were performed monocularly.

2.3. Subjects

Three groups were considered, and the characteristics are summarized below.

Group 1 (control) served as a normal reference and its measurements were performed in a vision laboratory using gratings of 1, 2, 4, 8, 12 and 24 c/deg (these data

were presented briefly before [25]). As the goal was to set up curves that would enable us to detect visual anomalies, we established that their subjects had to have a visual acuity of 6/6 with their best corrected refraction and no visual disorders or unsolvable refractory problems that could actually mask pathologies in their visual systems. All candidates had to undergo a thorough ocular media examination (biomicroscopy of cornea and crystalline) and fundoscopy, as well as an appropriate intraocular pressure control (contact tonometry) to rule out problems that could affect vision. An interview was also carried out to discard people that might have undergone any kind of ocular surgery, had a history of ocular disease, were taking any medication or drugs, and those who did not have good health or a normal development. The candidates were recruited from the neighbourhoods surrounding the university campus and all of them were naive regarding vision experiments and in the examination using this kind of equipment. Finally, according to the inclusion criteria, we considered 103 eyes of 55 subjects grouped in five age ranges: 20–29 (M = 25, SD = 3.5), 20 eyes; 30–39 (M = 34, SD = 1.7), 20 eyes; 40–49 (M = 44, SD = 3.6), 22 eyes; 50–59 (M = 55, SD = 2.9), 20 eyes; and 60–69 (M = 66, SD = 2.8), 21 eyes. Although all these people were free from ocular pathologies, some needed glasses in order to carry out the test. These subjects were corrected *in situ* by an optometrist who was present during the sessions. The process was carried out in a session in which first the right eye and then the left one were measured. When the observer had finished with the measurement of all the spatial frequencies of one eye he was given about three minutes to rest before beginning with the measurements of the other eye.

Group 2 (clinical) was made up of 29 subjects between the ages of 20 and 49 (M = 32, SD = 9.2) who voluntarily attended the Ophthalmology Service of the UNT Medical School for the first time because they recognized having some difficulty with their vision. Measurements were performed in a consulting room. These people were evaluated first with the psychophysical tests (Visual Acuity, VCTS 6500, and a computer-based CSF measurement system) and then had to undergo the standard examination routine in order to determine the diagnostic. If they were wearing any refractive correction, they performed the tests with them. The spatial frequencies of 1, 2, 4, 8, 12 and 24 c/deg were measured. For the analysis presented in this work, only were considered the data of one eye of each subject.

Group 3 (non-clinical) consisted of 56 subjects between the ages of 20 and 49 (M = 31, SD = 8.1) who were visitors to a Technology Fair (INNOVAR), a noisy and visually polluted environment. All had volunteered to perform the CSF test. They were to respond to a brief questionnaire oriented to getting to know about their health status and to discard visual problems. If necessary, they wore their own corrective lenses when performing the test. Observers with any evidence of pathology were not included. We checked their visual acuity by a test presented with the same equipment and then, as the intention was to use the test as a fast screening tool, we measured contrast sensitivity using only three spatial frequencies: 1, 4, and 12 c/deg. If a measurement showed a curve with a shape outside the normal values, we measured it again to check the results. As in group 2, only were considered the data of one eye of each subject.

3. Results

3.1. The CSF curves

According to GLYNN and ROSNER [38], unless the pairs of eyes in a subject are perfectly correlated, discarding data of one eye to satisfy the assumption of independence among eyes is an inefficient strategy. In order to study the data on an eye-specific basis, we performed on each age range of the group 1 (control) a regression analysis of the right *versus* the left eye, considering the variables *subject* and *spatial frequency*. All these fitted models were statistically significant ($p < 0.001$), showing that the measurements on the right and left eyes are not linearly correlated (with $p > 0.05$) in all the age ranges considered. The diagnoses of the fitted models showed that the errors were not correlated and present a normal distribution.

The contrast sensitivity curves are drawn for each age range. They are obtained from the calculation of mean values and the standard deviation for each spatial frequency (Fig. 1**a**).

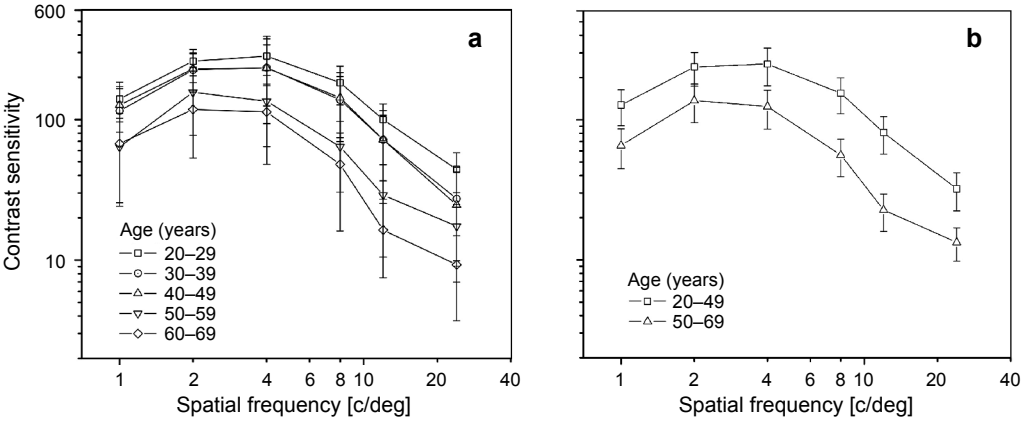

Fig. 1. Mean values of contrast sensitivity for each age range of the group 1 (control) – **a**; the two normality curves resulting from grouping the observers into 20 to 49 and 50 to 69 years-old ranges – **b**. In both graphs vertical bars represent one standard deviation.

It can be observed that the five curves follow the typical pattern of a band-pass filter. The curves for the two higher age-ranges are slightly separated from the other three, two of which – decades 30–39 and 40–49 – practically overlap.

3.2. The age-reference curves proposed for a clinical CSF system

As a lower number of CSF curves would be desirable for clinical usage, if we consider Fig. 1**a**, it can be easily seen that there would be a separation between the curves in the age ranges 20–49 and 50–69. Preliminary analyses indicated that the data

fulfilled the assumptions of normality and homogeneity-of-variance. In order to test these separations, a one way ANOVA for each spatial frequency was done, followed by a Tukey–Kramer method to determine which groups differ from each other. The ANOVA showed significant differences in all the spatial frequencies (1 c/deg, $F(4,98) = 13.46$; 2 c/deg, $F(4,98) = 15.06$; 4 c/deg, $F(4,98) = 9.39$; 8 c/deg, $F(4,98) = = 19.89$; 12 c/deg, $F(4,98) = 21.74$; and 24 c/deg, $F(4,67) = 6.08$, with $p < 0.001$ in all the cases). The *post-hoc* analysis using multiple comparisons found no significant differences between the ranges of 20–29, 30–39, and 40–49 for all the spatial frequencies, which also happened between the ranges of 50–59 and 60–69 (all the confidence intervals – with a confidence coefficient of 95% – were not significantly different from 0). This analysis also showed significant differences between the age ranges of 20–29, 30–39, 40–49 and those of 59 and 60–69. From this piece of information, the subsets were rearranged into two wider ranges of 20–49 and 50–69 years, and the ANOVA confirmed that both ranges were different for all the spatial frequencies: 1 c/deg, $F(1,101) = 12.94$, $p < 0.001$; 2 c/deg, $F(1,101) = 29.34$, $p < 0.001$; 4 c/deg, $F(1,101) = 16.12$, $p < 0.001$; 8 c/deg, $F(1,101) = 27.21$, $p < 0.001$; 12 c/deg, $F(1,101) = = 27.24$, $p < 0.001$; and 24 c/deg, $F(1,70) = 3.75$, $p < 0.1$.

As regards the highest frequency (24 c/deg), we found that for the 50–69 range only 12 of the 41 cases considered were able to take measurements, even though all of them passed the AV test. This is why we will not consider the value for the 24 c/deg spatial frequency in the drawing of this 50–60 year old normality interval. If normal older observers have difficulty in seeing the gratings for that spatial frequency, it is likely that the observers of the same age who have some pathology will not be able to see them either.

Figure 1**b** draws the two curves obtained according to the proposed regrouping. From the mean values and the standard deviations for each spatial frequency, the normality interval to be used for the detecting pathologies was calculated. In the clinical practice, it is common to set the normal intervals following the criterion that places the measurements' distribution average plus and minus two standard deviations [39], leaving a 95.4% probability between these limits. Applying such criterion to the curves in Fig. 1**b**, we obtained the graphs in Fig. 2 which show the superimposition of the normality areas for the 20–49 and 50–69 age ranges. In this way, these two references could allow us to determine the difference between normal people and those with a given visual problem. This is done by comparing the measured contrast sensitivity with the corresponding age-range normality intervals.

As we were interested in evaluating if this separation into two ranges of normality could increase the sensitivity of the test, especially when it comes to detecting deficits in the younger subjects, we performed a series of measurements in a clinical environment. As we stated previously, group 2 consisted of people with potential problems in their vision, and they attended an ophthalmology service for help. From the recruited subjects, clinical examinations showed that 35% had refractive problems, 52% showed

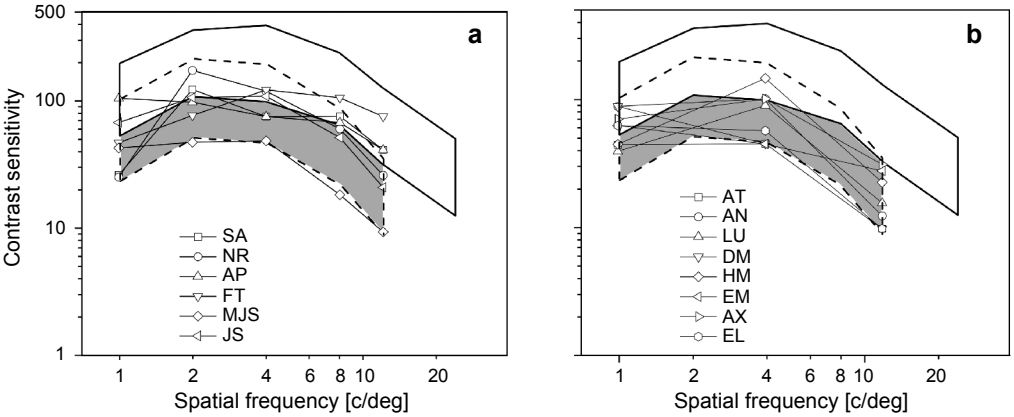

Fig. 2. Intervals of normality for the 20 to 49 years-old (solid line) and 50 to 69 years-old range (dashed line) obtained from the control subjects (group 1). The grey area indicates the difference when overlapping the normal areas for 20 to 49 and the 50 to 69 years old. CSF curves of subjects with two or more points in this area were plotted; group 2 (clinical) subjects – **a**, and group 3 (non-clinical) subjects – **b**.

some kind of pathology such as glaucoma or cataracts and 13% needed more studies to complete the diagnosis. From a total of subjects, 93% of the cases were correctly detected by the computer-based test as to having visual deficits. It is relevant to note that 22% of the detected cases were possible thanks to the separation of the normal values into two curves. Figure 2**a** shows that these subjects of 20 to 49 years who have two or more points falling into an area (marked in grey), that could be assumed as "normal" for them if a wide age range (20 to 69) were considered.

A vision test could possibly be used for screening. This consists in measuring a large number of people under different conditions to those found in labs or clinics, and in a short period of time. As has been established, group 3 consisted of non-clinical observers who, according to what they told us, had no visual problems. Those observers who needed refractive correction wore their own glasses. The 33% of the participants departed from the normal values. Based on the information gathered in the questionnaire, 63.6% of their deficits could be explained by refractive errors, but 36.4% of the participants needed a full clinical examination. Consequently they were all referred to an ophthalmologist. The same analysis that had been carried out on group 2 was performed on group 3. The 42% of the cases had two or more points falling in the grey area (Fig. 2**b**). These would not be considered abnormal if a range that did not consider the ageing changes were used instead.

4. Discussion

There is no doubt that contrast sensitivity is an exhaustive way of evaluating spatial vision. However, despite its continued use for research, the CSF has not been definitely established as a standard in the clinical practice as has been noted for years [22], per-

haps due to the number of variables that affect its determination. Also, the question of the age intervals considered previously in different works and the criteria applied to make (or not) its division into ranges can be added. All of these make the normal curves determined by a particular equipment unusable to explain other obtained with a different one, and turn necessary to explain how these references were determined. For instance, HIGGINS *et al*. [34] considered the same five age ranges as the ones we used and grouped 10 observers per range. Our results agree with the trends of the curves obtained by these authors with the method of adjustment but none with those obtained using the forced-choice method. Special emphasis should be put on the similarity of how the three upper curves are separated from the other two belonging to the younger observers. In this sense, the determination of normal age-related changes that affect the reference curves must be considered crucial for maximizing the specificity of the test.

From the statistical analysis we obtained two ranges of normality, whose significant differences appear around the 50's. This is more evident in Fig. 3**a** when plotting the contrast sensitivity for each spatial frequency as a function of age, because all the curves present a change in the slope at about range 40–49. This coincides with data reported by other authors [32, 40], although actual critical ages seem to vary between 45 and 60 years-old depending on the characteristics of the sample and the visual function considered. By confronting the obtained normal curves with measurements in clinical conditions and others that simulate a screening process (Fig. 2), we can observe that this division into two ranges allows a better discrimination, especially for young adults. Measurements show an improvement of approximately 20% in the detection capabilities of the test, even when only three spatial frequencies were considered (as in group 3).

The curves in Fig. 3**a**, aside from the rate in the change of contrast sensitivity, also point to another potential problem: the criteria in the selection of the older individuals

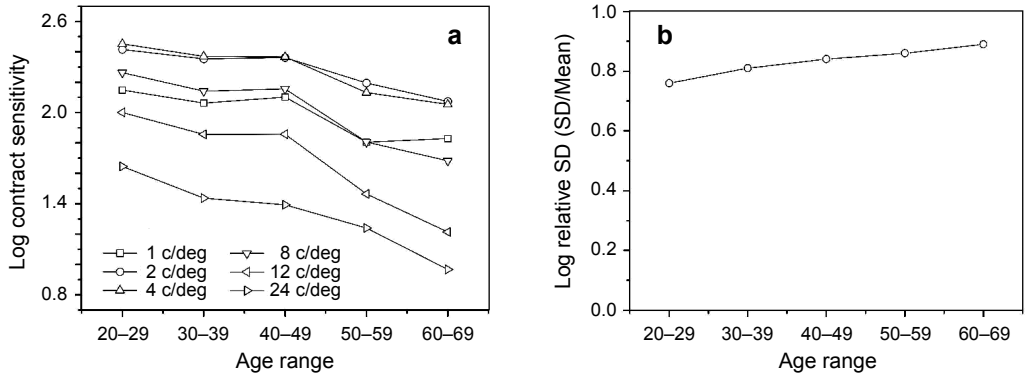

Fig. 3. From data of group 1 change of log contrast sensitivity for the sinusoidal gratings with spatial frequencies of 1, 2, 4, 8, 12 and 24 c/deg as a function of age range (**a**). Mean of the log relative standard deviation (SD) of all the measured spatial frequencies as a function of age range (**b**).

for normal reference. Although subjects were always screened by ophthalmological exams before their inclusion, this does not eliminate the deficits that have not as yet produced significant or macroscopic ocular changes. Its inclusion increases the within age-range variability because the CSF was proved to be very sensitive to small perturbations in the visual system. This variation can be seen in Fig. 1**a**, but to make it more evident, the relative standard deviation of all the spatial frequencies for the different age ranges was plotted in Fig. 3**b**. As noted, there is a monotonic increment in the ratio between the standard deviation and the mean as a function of age.

Epidemiologic data indicate that in the American continent most blindness and visual impairment still results from avoidable causes, such as cataract or refractive errors [41, 42]. Although small, our sample showed that about one third of the screened people had vision problems which could be due mainly to some of the aforementioned causes. More importantly, this result shows the usefulness of these CSF tests based on a flexible platform such as a PC as a screening instrument that can help in the detection of these cases.

The epidemiologic data and the variations plotted in Fig. 3**b** also raise the question of "what constitutes a normal reference group for subjects older than 60?". As pointed out by JOHNSON and CHOY [40], normal can mean "typical" or it can mean "healthy", but when we considered the elderly population where diseases are common, these two definitions must not be considered as equivalent. That is why the tests sensitive in detecting early signs of abnormalities in the visual system – like those that evaluate the CSF [43] – cannot tolerate the wide variability that characterizes the elderly population. For this reason we decided not to include people older than 70 as a normal reference, because it is difficult to define a subject that represents the average status of a person of this age.

5. Conclusion

In a previous work, we established the characteristics that a CSF measurement system ought to have in order to be used in ophthalmological clinics with special consideration to the advantages of this kind of computer-based equipment. We also suggested the necessity of having at least two normal ranges based on age. In the present work, we assessed this statement by considering the effects of the normal ageing process on the visual system. The discrimination provided by this separation into two ranges was tested with two groups of observers, showing an improvement of 22% in the detection of vision anomalies. We also tested the system's capacity to function as a fast screening tool by using only three spatial frequencies.

The results support the idea that a computerized system for contrast sensitivity tests of these characteristics can be used in clinics and in vision screening of the population, taking advantage of its intrinsic versatility.

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