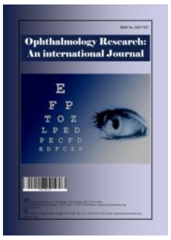

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Contrast Sensitivity Measurement Tests and Methods

George Karetsos[1] and Aristeidis Chandrinos[1*]

[1]Department of Biomedical Sciences, Division of Optics and Optometry, Laboratory of Optical Metrology, School of Health and Welfare, University of West Attica - Egaleo Park Campus - Athens, Greece.

Authors' contributions

This work was carried out in collaboration between both authors. Author GK performed the literature searches and the analysis. Author AC wrote the first draft of the manuscript. Authors GK and AC managed the structure of the paper. Both authors read and approved the final manuscript.

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ABSTRACT

Contrast is a measure of the amount of lightness or darkness an object has in relationship to its background. Usually, it is described as Contrast Sensitivity (CS), which actually is the inverse of the contrast threshold. More often than not, stimulus set includes grating patterns of various sizes that are presented in a stationary manner or are dynamically presented by reversing the contrast at different rates.
A variety of tests were developed, in order to asses and evaluate contrast sensitivity, in many different ways. A classical method, to check for contrast sensitivity, is the Pelli-Robson contrast sensitivity chart.
The Bailey-Lovie contrast sensitivity chart is another letter chart that deals with differences in the number of letters read on the high and low contrast charts, with a main drawback, the necessity to follow the size of the letters.
The Functional Acuity Contrast Test is designed to identify vision loss from a variety of disorders, many of which are not detected by high or low contrast Snellen Acuity tests. The MARS Letter Contrast Sensitivity Test shows good agreement with the Pelli-Robson test and possibly it may be the alternative to the Pelli-Robson chart, in clinical practice and research.

**Corresponding author: E-mail: achand@uniwa.gr;*

Keywords: Contrast sensitivity function (CSF); Pelli-Robson test; Bailey-Lovie CS test; MARS test; FACT test.

1. INTRODUCTION TO CONTRAST SENSITIVITY

The ability to detect the presence of an object depends not only to the size of the object, but also on the presence of any luminance differences between the object and its background. Contrast is a measure of the amount of lightness or darkness an object has in relationship to its background [1]. The smallest notable amount of difference in lightness and darkness, between an object and its background, illustrates contrast threshold.

The sensitivity to the above mentioned difference in luminance is recognized as contrast sensitivity. Nevertheless, contrast threshold is usually described as contrast sensitivity, which actually is the inverse of the contrast threshold. Frequently, contrast sensitivity is articulated in log units. Thereby the values are linear and the comparison of contrast levels is feasible. While the background luminance remains constant, is better to use the Weber principle (Fig. 1). In case that both light and dark components change, should be used the Michelson procedure [2,3].

Michelson equation: $$\frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}}$$

Weber equation: $$\frac{L_{\max} - L_{\min}}{L_{background}}$$

Fig. 1. Computing contrast sensitivity (*after Pelli and Bex, 2013*)

In most cases, evaluation of behavioural reactions to visual stimuli is appropriate to measure visual function. Snellen acuity is the standard measure in everyday clinical practice. But this measure provides only some degree of information about the visual system function.

Furthermore, visual acuity does not provide information on a person's ability to detect the lower spatial frequencies that also contribute to overall pattern vision, and that may be selectively affected as the result of eye disease. Most recently, a better method to consider visual function was implemented, the contrast sensitivity testing [4].

The alternative contrast sensitivity test uses grating patterns to determine the lowest contrast sensitivity, detected by a patient for a given size of pattern by simulating their normal environment.

More often than not, stimulus set includes grating patterns of various sizes that are presented in a stationary manner or are dynamically presented by reversing the contrast at different rates [4,5]. The MARS Letter Contrast Sensitivity Test generally was used in low vision, exhibits good agreement with the Pelli-Robson test and its likely to replace the Pelli-Robson chart in clinical practice and research in the near future.

2. CONTRAST SENSITIVITY FUNCTION

Contrast sensitivity is impaired in many clinical conditions and peak contrast sensitivity may be reduced even when acuity is normal [3]. The plot of contrast sensitivity vs. spatial frequency (Fig.2) is called the spatial contrast sensitivity function (CSF). This contrast sensitivity function (CSF) typically consists of the measured contrast detection threshold at five or so spatial frequencies uniformly spaced on a log scale spanning the most sensitive part of the range, typically 1 to 16 c/deg. Normally, two types of test stimuli have been used to measure contrast sensitivity: gratings and letter charts.

The most suitable stimuli to isolate the low-level analysers that believed to underlie pattern vision, are the Gratings [6].

One of the most famous of these types of stimuli is known as the 'Gabor patch': a sine-wave grating. Frequency and orientation representations of Gabor filters are claimed by many current vision scientists to be similar to those of the human visual system [7].

Vision is a behavioural phenomenon, and so in order to measure the output of the entire visual system similar sinusoidal grating patterns, like Gabor patches, can be used as input signals.

Note that this curve, in Fig 2, is not lowpass, as would be expected from a simply optical system [8]. Instead, it peaks at an intermediate spatial frequency (usually about 4 cycles per degree) and decreases in contrast sensitivity at lower and as well as higher spatial frequencies. On the other hand, have in mind that as the contrast threshold decreases, the contrast sensitivity increases.

2.1 Visual Acuity and Contrast Sensitivity Function

In the human visual system, the minimum angle of resolution in minutes of arc is inversely proportional to visual acuity (VA) expressed in a decimal scale [9].

Typically, clinical tests of visual acuity consist on determining the size threshold for a recognition task. The targets to be recognized are called optotypes and they comprise letters (or numbers) designed so the width of the strokes and gaps are one fifth of the height of the optotype character [9]. World Health Organization (WHO) estimates a good VA expressed in minimum angle of resolution (MAR) to be “1” [10]

Currently, if we return to the CSF (illustrated in Fig. 2) and consider its relation to visual acuity, it is notable that high frequency limb of this curve intercepts the spatial frequency axis at the point that the contrast sensitivity falls to a value of 1.

In Snellen notation, an acuity of 6/6 corresponds to a grating acuity of 30 cycles per degree, which means a bar width of one minute of arc

It is good to have in mind that when the contrast sensitivity is 1, its reciprocal contrast threshold is also 1. Consequently, this cut-off point is an estimate of grating acuity. Therefore, visual acuity testing measures only one point on the CSF.

As a result, an acuity measure does not indicate how well a person can see large or medium sized objects and the implied assumption, that if a person’s acuity is normal then the person is able to see large objects well, is probably false.

On the other hand, patients with identical visual acuities may have greatly different CSFs. For example, tests performed by Ginsburg et al. (1992) on Air Force pilots in flight simulators showed that performance level was predicted by the pilots’ CSFs, but not by measures of their acuity The CSF therefore provides a more accurate assessment of visual functioning in the real world than does visual acuity testing.[11,5,12].

2.2 Aging and Contrast Sensitivity Function

Owsley et al. (1983) described the association between selective losses in high spatial frequency information in mature population with increasing age [4]. This contrast sensitivity deficit is presumably caused by optical factors. Otherwise, it is desirable to assess visual functioning in infants [13]. While the visual system is in an early stage of development, diagnosis and treatment may mean prevention of a permanent neural deficit later in life. Newborns, obviously, are unable to follow instructions and respond appropriately.

Many years ago, conversely, researchers discovered that infants prefer to look at more complex visual stimuli [13,14]. This means that given them the choice to look at a grating pattern or a homogeneous field, they will look at the pattern.

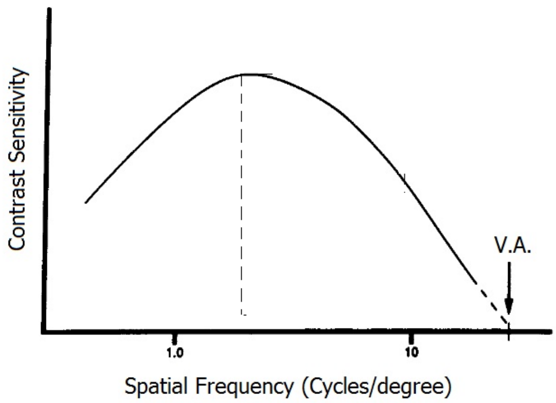

Fig. 2. Typical CSF. Peak occurs at a spatial frequency of about 4 cycles/degree. Note, the point that the curve intercepts the abscissa (spatial frequency axis) is the estimate of visual (grating) acuity (*Modified after Jindra and Zemon (1989) J Cataract Refract Surg.*)

2.3 Psychophysical Testing

Sensory stimulation is the application of environmental stimuli by an external agent for the purpose of promoting arousal and behavioural responsiveness. The visual stimulus, normally is a stimulus in the form of a picture or colour, shown on a screen. To date, a variety of psychophysical methods were developed in order to measure a threshold response.

In the technique known as the method of adjustment, the observer is asked to adjust the intensity of a stimulus, such as the contrast of a grating pattern, until the stimulus is barely perceptible. This intensity value is recorded as the threshold for that particular stimulus.

In other techniques, known as the method of constant stimuli and method of limits, the observer is asked to indicate whether a stimulus is perceptible or not by answering "yes" or "no". Thresholds are then defined as the intensity that produces the transitions between yes and no responses. All these methods are subjective. They depend on the honesty and reliability of the patient, and the accuracy of the responses cannot be verified. Most people have a strong bias for saying either yes or no, producing large differences between individuals that are based on no sensory factors [15,5,16].

3. MEASURING CONTRAST SENSITIVITY

The basic principle used in measuring contrast sensitivity has long been related to the analysis of various physical systems. If the real object consists of a pattern with a contrasting background, such as a sine wave grating, then the ratio of the imaged contrast to the real object contrast can be measured [17, 18].

In term of physics, a commonly used measure to evaluate the performance of optical systems is the modulation transfer function (MTF). The modulation transfer function is the magnitude response of the optical system to sinusoids of different spatial frequencies. When we analyse an optical system in the frequency domain, we consider the imaging of sine wave inputs, like the ability of a lens to transfer contrast at a precise resolution from the object to the image. So MTF is a way to integrate resolution and contrast into a single specification. On a line test target, as spacing decreases, it is difficult for the lens to transfer this decrease in contrast, while MTF decreases. In that way, MTF does not correspond fully to analyse the contrast of the image created in the human visual system [17].

In a sine wave grating (Fig.3), the luminance of the bars varies sinusoidally over space, and can stand out along the dimensions of spatial frequency, the amount of contrast, and the orientation. For more than 30 years, vision researchers have begun to speculate that human visual system has features that suggest the existence of multiple neural spatial filters. Each filter has specific spatial tuning characteristics [19,14].

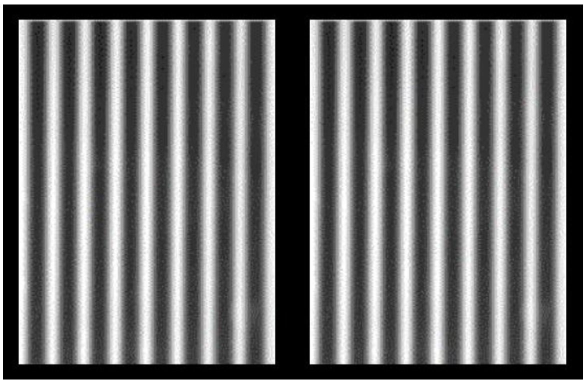

Fig. 3. Sine sinusoidal single frequency gratings

Nowadays, testing contrast sensitivity is even more essential than visual acuity and universally is acknowledged as balancing visual acuity, because it reveals the quality of vision and likely turns down fairly early, while visual acuity stay on rather normal [5].

As a result, contrast sensitivity testing is a powerful new tool for determining the capability of the visual system to transmit or filter spatial and temporal information about the objects we see. In practice, it measures the least amount of contrast that is needed to detect a visual stimulus.

3.1 Contrast Sensitivity testing

Custom eye exam does not include contrast sensitivity testing. The ordinary way to check for this is using a Pelli-Robson contrast sensitivity chart (Fig.4)**.** The chart includes horizontal lines of uppercase letters, all in the same size. This type of vision test is usually performed while the patient wears his eyeglasses or contact lenses.

From left to right, the contrast of each letter will decrease. The patient starts from the top of the chart and reads each row until they can no longer see any letters against the white background.

The MARS Letter contrast sensitivity test uses a similar chart as the Pelli-Robson test, except that the chart is smaller and viewed at a closer distance.

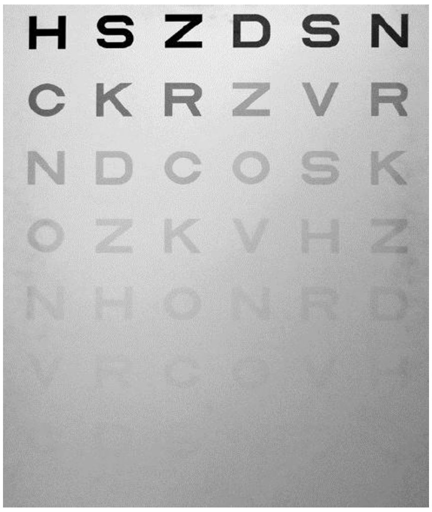

Fig. 4. Pelli-Robson test measures contrast sensitivity using a single large letter size (20/60 optotype), with contrast varying across groups of letters

3.1.1 Sinusoidal grating patterns

To evaluate the entire range of spatial vision, sinusoidal grating patterns are typically used as stimuli (Fig.5). These patterns are considered the most elementary because they can pass through an optical system without incurring a change in shape [17}**.** In addition, based on work published in the 1800s by the French mathematician Fourier [20], we know that any arbitrary visual scene (complex two-dimensional pattern of light) can be synthesized by summing an appropriate set of these one-dimensional grating patterns (varying in bar width, contrast, orientation, and relative position in the field).

3.1.2 Sine-wave gratings are used for accurate testing

A true contrast sensitivity test uses sinusoidal patterns, which vary in luminance across a grating pattern (see image below). The luminance of the grating is varied from 0.5% contrast to 90% contrast. Contrast sensitivity determines the lowest contrast level, which can be detected by a patient for a given size of the grating pattern. The different size gratings are called spatial frequencies.

Thus, sinusoidal grating patterns, because of their elementary character as a stimulus, are the best stimuli for assessing the optical processing of visual signals.

4. CURRENT TESTS FOR CONTRAST SENSITIVITY

4.1 The Bailey-Lovie Chart

These charts standardized the test task so that the size is the only significant variable from one row to the next. There are 5 letters per row, the between-letter and between-row spacing is equal to letter size, size progresses by a constant ratio (0.1 log unit = 1.26x), and letter difficulties are balanced for each row. The difference in the number of letters read on the high and low contrast charts provides a measure of the slope of the Contrast Sensitivity Function. The charts come as a set of two panels (21x24inches, 53x60cm) each with a high contrast chart one side and a low contrast chart (18% Weber or 10% Michelson) on the other.

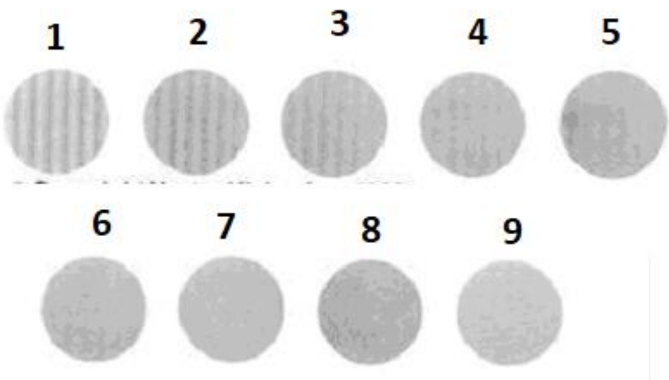

Fig. 5. Sinusoidal grating patterns (*modified after Vector Vision, Inc.*)

Fig. 6. The Bailey-lovie contrast sensitivity chart

The optotype set is the family of the British Standard (BS:1968) 5×4 non-serif letters. There are 14 rows with a range of sizes from 38 to 1.9 M-units (Fig.6). Sizes are given in Snellen units (in both feet and metric units), as well as visual acuity values in LogMAR and VAR (Visual Acuity Rating) for a 6-meter viewing distance.

Any other viewing distance may be used, as well. A scale printed on each chart provides the score adjustment for different test distances. With the LogMAR and VAR scales, equal credit is given for each additional letter read (each extra letter earns -0.02 with LogMAR, or 1 point with VAR).

4.2 VCS and FACT tests

Real-world vision is not always high contrast black and white. Rather, it consists of objects having a wide range of sizes viewed under a variety of visually degrading conditions, such as fog, nighttime, bright sun, etc. Many visual disorders will show more significant vision loss under these conditions.

VCS testing, by itself, is generally not diagnostic for any specific condition (including either mold or neurotoxin exposure), but a positive result may suggest the existence of a health and life-affecting clinically obvious or hidden underlying cause. [18]

Visual contrast sensitivity (VCS) testing measures the ability of detecting details at low contrast levels and is often used as a nonspecific test of neurological function.

By and large, a VCS test involves the presentation of a series of images of decreasing contrast to the test subject and the recording of the contrast levels where patterns, shapes, or objects can or cannot be identified (Fig.7). The results of the test can then be used as an aid in the diagnosis of visual system dysfunction.

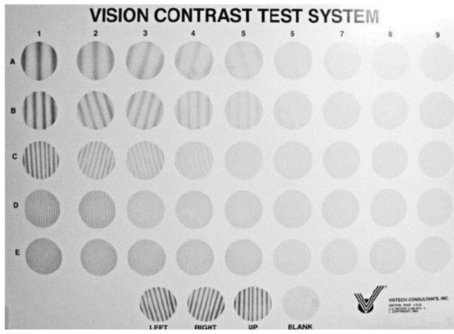

Fig. 7. The VCS sine-wave grating chart tests five spatial frequencies (sizes) and nine levels of contrast

The VCS test available now is a second-generation test from what was initially invented. It is an Online Contrast Sensitivity Test (OCST) and not a printed-paper test as it was originally developed. VCS contrast sensitivity tests are widely used by healthcare professionals, and researchers all around the world. Moreover, OCST test images are generated dynamically in software, which ensures that the images are of the highest quality and that the test is different each time you take it.

The Functional Acuity Contrast Test (FACT) is designed to identify vision loss from a variety of disorders, many of which are not detected by high or low contrast Snellen Acuity tests. FACT evaluates more effectively patient's vision over a range of size and contrast, which closely simulates their normal environment.

The progression of the high quality sine-wave grating size (Fig.8) changes in steps equal to one octave (i.e., a factor of two) between rows A, B, C and D and half octave between rows D and E. The corresponding spatial frequencies are 1.5, 3, 6, 12 and 18 (cpd). The contrast step between each grating patch is 0.15 log units. The gratings are tapered into an average gray background to eliminate ghost images (aliasing) and keep the mean retinal illumination constant. The grating patch size, 1.7 degrees, exceeds the size of the macula (1 to 1.5 degrees). The gratings are tilted +15˚, 0˚ and -15˚ to keep them within the orientation bandwidth of visual channels.

4.3 Contrast sensitivity Test Chart 2000

This chart appears similar to the Pelli-Robson test. Patients are required to read triplets of letters of decreasing contrast (Fig.9). The minimum contrast required for the patient to read 2 out of the 3 letters is recorded as the contrast sensitivity. This measurement is particularly valuable for patients with cataracts and various neurological conditions such as glaucoma

Thayaparan and colleagues (2007) concluded in their study that the electronic test chart does not agree well with the Pelli–Robson chart, although this might simply be due to the performance of liquid crystal display screens at low contrast levels [21].

Channa, in his recent study (2014), found a significant difference between the scores from the computerised Test Chart 2000 and the Pelli-Robson chart. Test Chart 2000 generated a higher contrast sensitivity threshold when compared to the Pelli-Robson test. [22]

4.4 MARS Test

Eye care professionals and clinical researchers around the globe, implement the quickly dispensed Medication Adherence Report Scale (MARS) test, for accurate and convenient contrast sensitivity measurements [23]. This test, evaluates visual acuity using low contrast targets. So, the MARS tests are *true contrast sensitivity* tests that patients can perceive, sooner than the smallest letters they can identify at some low, randomly chosen contrast. By MARS tests, it is the contrast, and not the letter (or numeral) size that reduces from the beginning to the end of the chart.

In general, these tests are used to assess and monitor functional disability in low vision. Also, MARS tests are applied to carry out clinical trials for refractive surgery and cataract or to examine functional effects of eye disease progression. Furthermore, to identify functional losses in low contrast perception associated with optical and neural discrepancy [23].

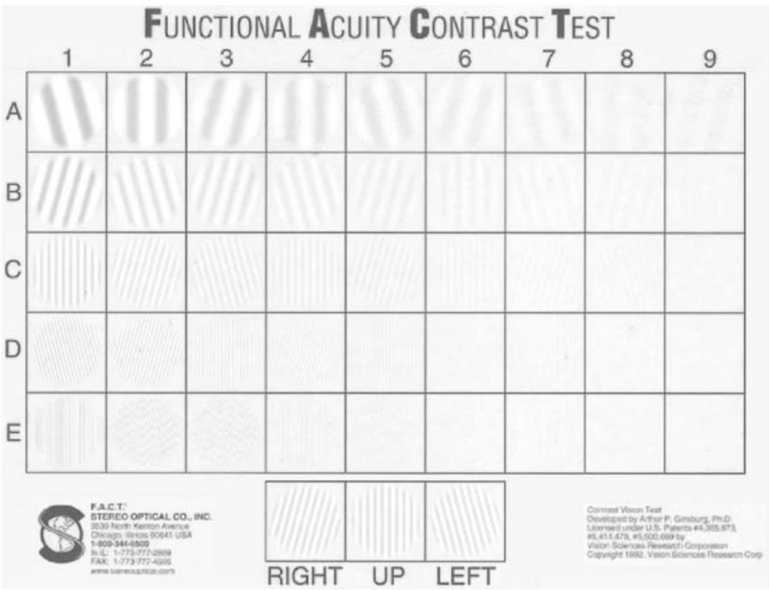

Fig. 8. The functional acuity contrast test (fact) chart

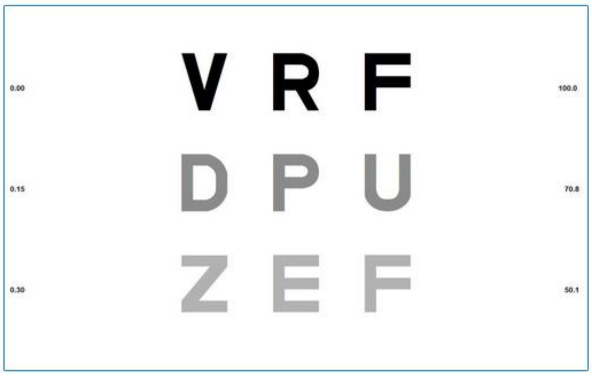

Fig. 9. The test chart 2000 for CS evaluation

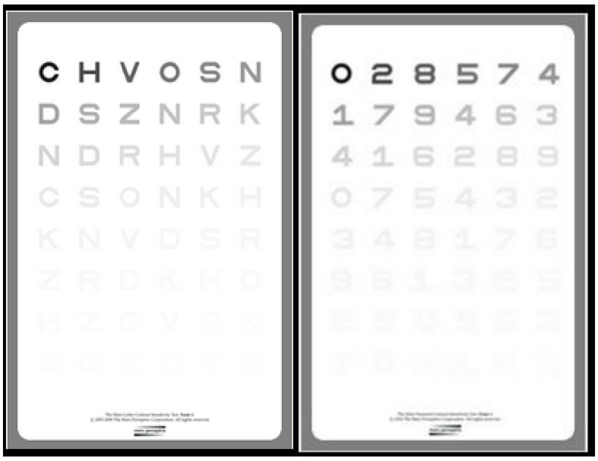

Fig. 10. The Medication Adherence Report Scale (MARS) test in letter and numeral versions (*modified after mars perceptrix website*)

MARS tests are hand-held and designed for convenient near-vision testing.

Each chart is printed with 48 *different* contrast levels, fading gradually in 0.04 log unit steps. Generally, testing *and* scoring time is under a minute per eye. Offered in both letter and numeral versions (Fig.10), include three charts, for the left eye, right eye and binocular testing. According to Dougherty et al, (2005), Mars Letter Contrast Sensitivity Test shows good agreement with the Pelli-Robson test and similar test–retest repeat ability. These findings suggest that it may be a practical alternative to the Pelli-Robson chart for testing Contrast Sensitivity, in clinical practice and research [22,24].

4.5 The Freiburg Visual Acuity and Contrast Test (FrACT)

Nowadays, in order to evaluate even more accurately and precisely the contrast sensitivity, appropriate computer assisted programs have been developed. On the other hand, computer assistance provides a considerable reduction of confounding influences. FrACT is currently available in nearly any kind of computer and can be displayed in both CRT-or LCD-type VDUs, using a luminance of the Landolt C (Fig.11) between 80 and 320 cd/m^2 at a contrast of 85%, with a scoring time less than 2 minutes[25], Landolt C optotypes are presented on the computer screen.

FrACT can be seen as an automated alternative to ETDRS, extending its range both at the upper and lower end and being safe from being learned by heart on repeated testing.

5. FACTORS THAT AFFECT CONTRAST SENSITIVITY

A common factor influencing many forms of visual sensitivity is the size of the target in the visual field. In contrast sensitivity testing, the sensitivity at a particular spatial frequency is dependent upon the number of cycles included in the sine wave pattern, with sensitivity increasing with the inclusion of more cycles [26]. Additionally, at lower spatial frequencies, the temporal characteristics of the grating stimuli (e.g., duration of the grating exposure and the rate of onset) can affect the contrast sensitivity function [25].

Another factor known to impact contrast sensitivity testing is illumination. Indeed, the shape of the contrast sensitivity function is itself a result of the perceptual system's requirement for increased illumination for resolving textures of higher spatial frequencies. As mean illumination is lowered, the frequency of the peak sensitivity and the height of the function are correspondingly lowered [24].

6. DISCUSSION

Contrast is a measure of the amount of lightness or darkness an object has in relationship to its background. Vision is a behavioural phenomenon, and so the human observer must physically respond to each stimulus in order to measure the output of the entire visual system. Real-world vision consists of objects having a wide range of sizes viewed under a variety of visually degrading conditions. Visual contrast sensitivity test measures the ability of detecting details at low contrast levels. Contrast sensitivity testing determines the capability of the visual system to transmit or filter spatial and temporal information about the objects we see.

A variety of tests were developed, in order to asses and evaluate contrast sensitivity, in many different ways. The most popular test are demonstrated in Table 1. A classical method to check for this is the Pelli-Robson contrast sensitivity chart. An alternative contrast sensitivity test uses sinusoidal patterns, which vary in luminance across a grating pattern from 0.5% contrast to 90% contrast. These patterns determine the lowest contrast level, which can be detected by a patient for a given size of pattern because these stimuli can pass through an optical system without sustaining a change in object's shape.

Fig. 11. The FrACT$_{10}$ Test screens (*Modified after https://michaelbach.de/fract/*)

Table 1. Comparison table for the most popular contrast sensitivity tests (*modified after Richman et al., 2013*)

Test	Target type	Range of contrast (%)	Answer choices	Usage
Pelli-Robson	Letters in uniform size	0.56 - 100	10	contrast sensitivity testing
CSV-1000	Sine wave gratings (4 frequencies)	0.5 - 67.6	2	test of neurological function
FACT (Optec)	Sine wave gratings (5 frequencies)	0.56 - 25	3	to identify vision loss
MARS	*Letters and numbers* In uniform size	1.2 – 91.2	10	Functional disability in low vision

Bittner, Jeter and Dagnelie (2011), in a study about the grating visual acuity and contrast sensitivity tests concluded that computer-driven grating tests appear to be reliable, capable of evaluating vision that may fall outside of the range of standard clinical tests and may be useful during clinical trials for advanced eye disease [27].

Patients it is possible to have decreased contrast sensitivity despite normal visual acuity depending on which spatial frequencies a disease may affect. For that reason, researchers have often tested multiple spatial frequencies within the contrast sensitivity function (CSF) curve (Fig.2). On the other hand, to test full CSF curve is probably time consuming.

The Bailey-lovie contrast sensitivity chart deals with differences in the number of letters read on the high and low contrast charts and provides a measure of the slope of the Contrast Sensitivity Function. The charts come as a set of two panels each with a high contrast chart one side and a low contrast chart on the other. Main negative aspect of the chart is the necessity to use the size of the target.

VCS contrast sensitivity tests are widely used all around the world during the last decades. A more complex version is the Functional Acuity Contrast Test (FACT) that evaluates patient's vision over a range of size and contrast by simulating their normal environment. FrACT is a contrast sensitivity test including visual acuity test and providing computer screens with faded Landolt C optotypes.

The MARS Letter Contrast Sensitivity Test that mainly was used to assess and monitor functional disability in low vision, shows good agreement with the Pelli-Robson test and demonstrates similar test–retest repeatability (Table 1). These findings, published by Dougherty et al (2005) suggest that it may be a viable alternative to the Pelli-Robson chart for testing CS in clinical practice and research [24], as the repeatability of a visual acuity or CS test is always related to the number of letters per unit, which change in size or contrast [27]

7. CONCLUSIONS

This review deals with the most popular contrast sensitivity tests, The vast majority of these tests were developed, in order to asses and evaluate contrast sensitivity, in many different ways.

Nevertheless, the classical method to assess contrast sensitivity is the Pelli-Robson CS chart. On the other hand, the Bailey-Lovie contrast sensitivity chart deals with differences in the number of letters read on the high and low contrast charts. Main negative aspect of this chart is the necessity to use the size of the target.

The alternative contrast sensitivity test uses grating patterns to determine the lowest contrast level, which can be detected by a patient for a given size of pattern. These tests evaluate patient's vision over a range of size and contrast by simulating their normal environment.

The MARS Letter Contrast Sensitivity Test generally was used in low vision, but even though shows good agreement with the Pelli-Robson test. Possibly, it may work as an alternative to the Pelli-Robson chart in clinical practice and research

Visual contrast sensitivity testing measures the ability of detecting details at low contrast levels and determines the capability of the visual system to transmit or filter spatial and temporal information about the targeted objects. Nevertheless, there is no pattern of CSF loss that is distinctive to any particular vision disorder. The types of CSFs measured in patients with glaucoma or macular disease can be similar to the CSFs measured in cataract patients, although detailed analyses with targets of different size or at different retinal eccentricities may help differentiate between various causes of the loss.

Many researchers believe that contrast sensitivity tests are more sensitive to early eye disease than visual acuity. If this is true, then the apparent difference in sensitivity is probably due to careless measurement of visual acuity.

Although Bailey–Lovie charts were substituted by Pelli-Robson CS charts, which use letters with varying contrast across groups of letters, the CVS and FACT tests are widely used for assessing contrast sensitivity for various vision disorders.

Lately the new MARS Letter Contrast Sensitivity Test it may be a viable alternative to the Pelli-Robson chart for testing CS in clinical practice and research.

In conclusion, contrast sensitivity loss does not always specify a diagnosis, as many diseases generate similar effects on contrast sensitivity function. Nevertheless, contrast sensitivity testing is valuable to identify ocular disease and possibly lead to a treatment.

CONSENT

It is not applicable.

ETHICAL APPROVAL

It is not applicable.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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