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Psychophysical aspects of contrast sensitivity*

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Abstract

This paper reviews the psychophysical aspects of contrast sensitivity which concerns components of visual stimuli and the behavioural responses and methods used in contrast sensitivity testing. Some discussion is included of the different types of contrast sensitivity charts available as well as a brief background on the different types of graphical representations of contrast sensitivity and contrast visual acuities. Two illustrations also demonstrate stereo-pair representation of contrast visual acuities in the context of diabetic eyes. The doctoral research of the first author (AYS) that applies similar idea to understanding both inter- and intra-ocular variation of contrast visual acuities.

Key words: contrast, contrast sensitivity, contrast visual acuity, vision science, vision psychophysics, stereo-pair scatter plots, multivariate statistics

Introduction

Psychophysics is a scientific discipline designed to measure internal sensory and perceptual responses to external stimuli[1]. Sensory stimuli and behavioural responses are the defining or crucial concepts in determining contrast thresholds (for example, visual stimuli are used in chart-based contrast sensitivity measurements). These two concepts (visual stimuli and behavioural responses) together with different types of contrast sensitivity tests and their graphical representations will be discussed here.

1. Visual stimuli

Theoretically, any visual stimulus, pattern, or image can be decomposed into sinusoidal components (namely spatial frequency, contrast, spatial phase, and orientation) by means of Fourier analysis. Fourier analysis is an analytical method that calculates simple sine-wave components whose linear sum forms a given complex image[2, 3]. The visual stimuli typically used in contrast sensitivity testing consist of sine-wave or square-wave gratings whose luminance perpendicular to the bars is modulated in sinusoidal or square-wave form about a fixed mean level. Sometimes other stimuli such as letters are used and the limb or element width is used in converting to spatial frequency (see Figure 1 below). Perception of these bars as a function of spatial frequency is used to determine contrast threshold[2, 4]. The four components defining visual stimuli are as follows:

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a. Spatial frequency

Spatial frequency is defined as the number of image cycles that fall within a given spatial distance, typically one degree of visual angle and measures the fineness or coarseness of the grating[3]. One cycle consists of one light region (bar or line) plus one dark region or bar, for example, within a sine-wave grating[3]. A grating of high spatial frequency contains many narrow bars, that is, many cycles within each degree (cpd) of visual angle. A grating of low spatial frequency contains wide bars or few cycles per degree of visual angle. Spatial frequency can also be defined in terms of viewing distance; therefore as the viewing distance decreases each bar casts a larger image, hence spatial frequency decreases[1].

Snellen letter acuity can be expressed or converted into spatial frequency as illustrated in the figure below (Figure 1) [5]. At a six (6) metre (or 20 ft) distance, the Snellen denominator is divided into 180 (or 600 ft). Thus 6/60 = 180/60 = 3 cpd and 6/6 (or 20/20) converts to 30 cpd.

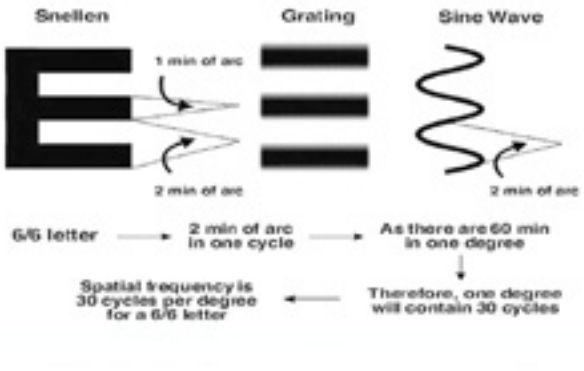

Figure 1. Conversion of Snellen notation to spatial frequency (Figure reproduced with permission of Webvision) [5].

b. Contrast

Contrast is a measure of how different a luminance level at some point in space or time is, compared to some luminance reference. Spatial contrast compares some portion of the visual field with another portion, for example, the intensity difference between the light and dark bars[6]. Mathematically, contrast for sine-wave gratings is calculated using two parameters, maximum ($L\max$) and minimum ($L\min$) luminance, both of which can be measured physically. Sine-wave grating or periodic charts use the Michelson formula:

$$Contrast = \frac{L\max - L\min}{L\max}. \quad (1)$$

To calculate contrast with non-periodic or letter charts the Weber formula applies:

$$Contrast = \frac{L\max - L\min}{L\max} \quad (2)$$

where $L\min$ is the luminance of the lighter part, and $L\min$ is the luminance of the darker part. By multiplying these ratios by 100, the percentage contrast of a particular stimulus is represented. Although the luminance has units such as candelas per square meter, contrast is a dimensionless number[1, 6].

c. Spatial phase

Spatial phase refers to a grating's position relative to some landmark or reference. Edge-like and line-like features result from maximal local phase coherence[4].

d. Orientation

Orientation refers to the relative physical position of the gratings, specifically the tilt which can be horizontal, vertical or oblique[4].

2. Behavioural responses and methods

Behavioural responses and methods are used to determine contrast thresholds. Contrast-detection threshold is an important psychophysical method used to measure the sensitivity of the visual system[1]. Contrast threshold is defined as the statistical contrast boundary below which contrast is too low for an image to be reliably detected and above which contrast is high enough for frequent image detection[3]. Four types of variability of threshold measurements have been identified. They include random fluctuations in the visual stimulus, continual random fluctuations in neural activity when visual signals are carried from the retina to the visual cortex, the subject's level of alertness or attention and the subject's psychological bias[3, 5]. Behavioural methods and responses are designed to minimize variability of threshold measurements[3, 5].

1.1. Behavioural responses

Behavioural responses are classified into criterion dependent and criterion-free methods.

a. Criterion dependent methods

Awareness of the presence or absence of a signal or stimulus, which engages the subject to respond

either affirmatively (that is, yes) or non-affirmatively (no) is classified as a criterion dependent method. Correct responses can range from 0% to 100%. Results can be plotted as a percentage seen *versus*, (for example), stimulus intensity resulting in an *S*-shape (*ogive*) psychometric function, which is also known as a *frequency-of-seeing* curve (see Figure 2). In criterion dependent methods a psychometric function can estimate the threshold (for stimulus intensity, for example, in candelas) as the 50% point on the curve[1, 5, 7].

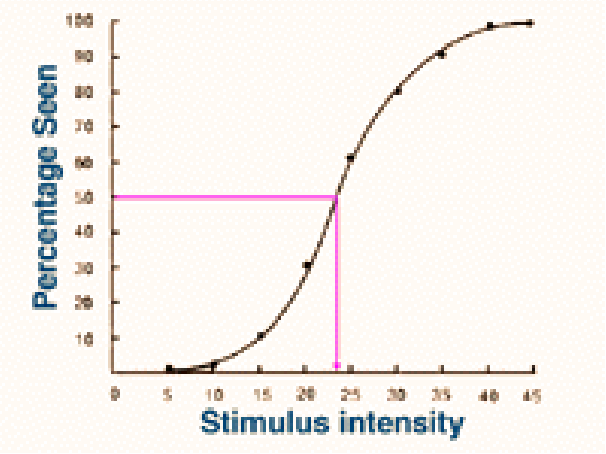

Figure 2. An ogive curve or psychometric function where a criterion dependent method was applied is illustrated here - only *yes* or *no* responses to the presence of stimuli of variable intensity were required. The threshold value is defined where 50% of the stimuli are detected, and in this figure the stimulus intensity threshold is 23.5 (Reproduced with permission from Webvision) [5].

b. Criterion-free methods

In forced choice paradigms subjects are forced to select between two or more intervals/choices, one of which contains the stimulus or target. A two-alternative forced choice (2AFC) paradigm forces the subject to choose between two alternatives, a four-alternative forced choice (4AFC), between four alternatives, *et cetera*. The percentage correct for the various stimuli intensities is used to construct a psychometric graph. In a 2AFC method there is already a 50% chance of a correct response and therefore the threshold is considered as 75% (Figure 3). For a 4AFC (starts at 25% chance of being correct) threshold is considered at 62.5% (in between 25% and 100%). Thus, the more choices available the more reliable the responses will become and, for example, letter targets are useful as they provide a choice of 26 alternatives (or only a 4% chance of guessing a letter correctly). Other clinical charts may offer fewer alternatives and some charts may, for example, use 10 Sloan or British standard letters which have similar legibility[1, 5, 7].

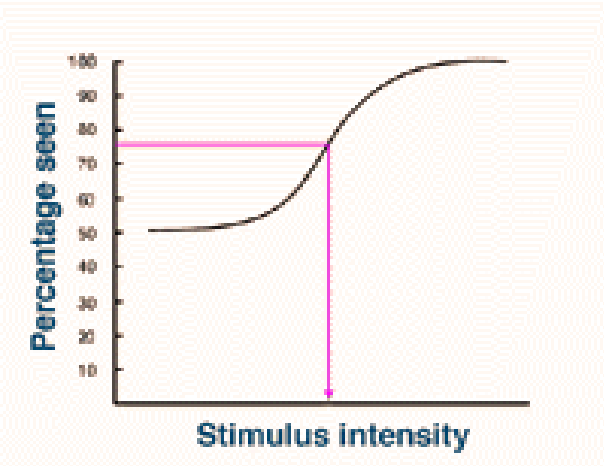

Figure 3. A 2AFC psychometric function with the threshold at 75% is shown (Reproduced with permission from Webvision) [5].

1.2. Behavioural methods

These behavioural procedures are classified into three types or methods:

a. The method of adjustment

According to Norton, Corliss and Bailey[1], this method is the simplest and most direct method for estimating thresholds. The method of adjustment is criterion dependent (yes/no responses). The subject adjusts the contrast level themselves until he or she can just see the stimulus (or is just unable to see the stimulus). The examiner begins each measurement by setting the initial value of the stimulus well above or below the anticipated threshold. The measurement procedure is repeated several times, and the mean is calculated. Elliot in Benjamin[7] reports that contrast threshold measurements from unseen to seen are higher when compared to those from seen to unseen. This is due to the effects of retinal ganglion cell adaptation, where the cells that respond to the grating or stimulus fatigue and reduce their response. Thus, this method is prone to two errors; one of habitation (when subjects develop a habit of responding to a stimulus) and two, of anticipation (when the subject prematurely reports to seeing the stimulus before the threshold has been reached) [5].

b. The method of limits

The method of limits involves the increasing (well above threshold) and decreasing of contrast in small

steps until the subject cannot detect the stimulus (known as descending limits). The method is then repeated in an ascending manner where the stimulus is first presented well below threshold and increased to reach threshold. The method is criterion dependent and the transition value is recorded. The mean value for all the trials is recorded as the threshold[5]. The method of limits is shown to be one of the most repeatable of all methods[7]. However, the limitations of habitation and anticipation are also relevant here. To minimize these errors, the method has been varied into *staircase* and *tracking* procedures:

In the staircase method stimulus intensity is progressively increased, as in ascending limits, until the subject sees the stimulus and the threshold is recorded. At this point the stimulus intensity is then progressively reduced (descending limits) till the subject is unable to see the stimulus. Thus, to reduce errors multiple simultaneous staircases are used. Threshold estimates are considered as the average of several reversal points, as calculated in the method of limits[1]. In tracking procedures the stimulus intensity is gradually raised and lowered (automated/computerized) at a smooth, constant rate. The contrast of the target is increased (ascending) from zero till the subject detects it, and thereafter the direction of contrast change reverses (descends). For example, if the stimulus was getting more intense, it then becomes less intense as a function of time. Thus, the stimulus value is always changing within the vicinity of the threshold value. The threshold is calculated as the average of the stimulus value at the reversal points[1]. The repeatability of this procedure has been shown to be poorer than either the method of adjustment or of the method of increasing contrasts [7]. Furthermore, Norton, Corliss and Bailey[1] report that subjects fatigue easily as stimuli may frequently cross the threshold in short periods of time, thus providing poor repeatability.

c. The method of constant stimuli

In the method of constant stimuli, random contrast levels are presented many times. Different sets of about 10-20 stimuli at the same contrast levels are used throughout the procedure. The percentage of correct detection is determined. In this method both criterion dependent and criterion-free modes can be utilised. In a 2AFC procedure, for example, the lowest point of the psychometric function should be 50% and threshold value taken as the 75% point on the curve[1, 7].

Contrast sensitivity tests

Numerous contrast sensitivity charts are commercially available and in this section only a few of the most commonly used clinical charts will be briefly discussed. Depending on the type of stimuli, contrast sensitivity tests can be divided into the following categories:

1. Sine-wave or periodic contrast sensitivity tests

Sine-wave, periodic, or grating tests, as discussed above consist of a repeated number of dark and light bars called cycles. The contrast sensitivity is determined by the lowest level of detection. Various types of grating tests are commercially available, however most of the tests (Functional Acuity Contrast Test (FACT), Sine-wave Contrast Test, and CSV-1000) are almost identical or a modification of the Vistech Contrast Test[7, 8].

The Vistech contrast chart is manufactured to be used at both distance or near (40 cm). The chart consists of circular plates arranged in five rows and nine columns. Across the rows spatial frequency varies (from 1.5 cpd in the top row to 18 cpd in the fifth row and 3, 6, and 12 in rows two to four). In each row sequential sine-wave gratings with different orientations and decreasing contrast from left to right across the nine columns are shown. Gratings are either tilted or vertical (and one can orient the chart differently to increase the possible range of orientations of the gratings). This test is in part criterion dependent (subjects are asked if they can see specific gratings) and also a 3AFC method (subjects are asked to correctly indicate the orientations of the gratings from the three alternatives)[7]. But, Owsley[9] concludes from various reports that the test-retest reliability of the chart is inconsistent especially for the purposes of screening and tracking contrast change. For example, in samples of unhealthy eyes reliability coefficients ranged from 0.3 to 0.6 depending on the spatial frequency and the coefficients were especially reduced at high and low spatial frequencies. Pesudovs *et al*[10] later confirmed these findings when repeatability and sensitivity of both the Vistech and FACT contrast sensitivity charts

were found to be ill-suited for refractive or cataract surgery outcomes research.

The CSV-1000 contrast test is a grating chart based test which has an internal retro-illuminated system. The chart presents 3, 6, 12, and 18 cpd spatial frequencies, with each row containing 17 circular patches. The test is criterion dependent, and uses 2AFC methods. Pomerance and Evans[11] reported that the CSV-1000 contrast chart was a clinically reliable tool for monitoring positive changes in glaucoma treated with beta-blockers.

2. Letter contrast sensitivity

Letter charts offer a large number of readily identifiable visual stimuli (of different spatial frequencies and limb orientations) which reduces the impact of subjective guessing. The Pelli-Robson, Mars Letter and the Test Chart 2000 (Thompsons Software Solutions, UK) charts are examples of letter contrast sensitivity. They consist of equally sized letters presented at different contrast levels[12-14]. The Pelli-Robson chart is probably the most commonly used chart administered at one (1) metre. The chart presents with 59 x 84 cm letters at 1 m (equivalent to 6/200) at 16 different contrast levels, arranged in eight rows of two triplets each. The contrast of each triplet decreases by a factor of 0.15 log units. The test therefore uses a 26AFC method and a letter-by-letter scoring method. The log contrast sensitivity is determined by the final triplet where the subject correctly reads two of three letters[12]. This test has been shown to have good test-retest reliability and repeatability[9]. Thus, this test has been used in large population studies including the Smith-Kettlewell Institute study[15].

The Mars Letter contrast sensitivity test is a modification of the Pelli-Robson chart, in that this method presents much smaller contrast decrements of 0.04 log units and is used at a proximal or near reading distance. In an evaluation study, the Mars Letter contrast sensitivity test showed excellent agreement and similar repeatability with the Pelli-Robson test. Advantages reported for using the Mars test include smaller size (22.8 x 35.6 cm *versus* 59 x 84 cm, and it is therefore easier to illuminate the chart uniformly), improved durability (printed on durable plastic sheet versus cardboard), and ease of use when compared with the Pelli-Robson method[13].

The Test Chart 2000 (Test Chart Xpert is a later version) is a test that presents various charts on a computer monitor or a flat panel display[14]. The letter contrast sensitivity chart is viewed at one metre, has ten different types of optotypes (including Sloan, British, Sheridan-Gardner letters, or Lea numbers or symbols) that can be displayed in triplets of decreasing contrast from top to bottom. Contrast sensitivity is measured when the patient can no longer read two out of the three letters displayed. Measurements can be recorded as log contrast sensitivity, contrast sensitivity or percentage contrast.

Comparison of the repeatability of the Test Chart 2000 contrast letter chart and Mars Letter chart was compared[16] to the Pelli-Robson test in 53 subjects with visual acuities ranging from 6/4 to 6/72. The results indicated that the Mars Letter chart showed better validity and reasonable agreement with the Pelli-Robson chart than that for the Test Chart 2000. The authors, however, suspected that the relatively poor performance of the Test Chart 2000 was due to the screen properties (the liquid crystal display screens projects a high luminance and thus the representation of low contrast levels may be suboptimal) rather than the Test Chart 2000 itself.

3. Low contrast acuity

This type of chart is a reduced contrast version of the visual acuity chart. These charts measure low-contrast visual acuity and not contrast sensitivity. Measuring contrast in these charts depends on visual acuity threshold. If the subject reports to only seeing the large letters at the top of the chart the score gives an indication of intermediate spatial frequencies, whereas smaller letters indicate higher spatial frequencies. Low-contrast visual acuities indicate the slope of the high frequency end of the contrast sensitivity function (CSF)[7].

The Bailey-Lovie chart uses 4 x 5 British standard letters. The chart consists of the same number (five) of letters and a uniform logarithmic progression in size of letters on each line. This layout ensures that relative crowding and contour interaction remain the same for each line. The test uses a 26AFC method with five decisions at each acuity level, scored letter-by-letter. These design characteristics enables the test to be reliable and repeatable. Thus, these types of contrast charts are approved by the National Eye Institute of the United States of America and

are standardized for contrast acuity measurement and recording[17]. The Early Treatment Diabetic Retinopathy Study (ETDRS), low-contrast Sloan letter charts and Regan low contrast charts have adopted the above standardised chart characteristics with slight modifications. For example, Regan charts use different letter font configuration with eight letters per acuity row.

The Test Chart 2000 Xpert also generates charts to measure low contrast acuity based on a five letters (there are ten different types of optotypes from which to choose), and uniform progression in size of letters per line format. The contrast of the chart can be adjusted between 0 to 100% and can be displayed in LogMAR, Snellen or single letter format[14]. A study conducted by Ehrmann, Fedtke and Radic[18] cross-validated high and low contrast visual acuity data measured using paper charts (Bailey-Lovie chart at 90% and 8% contrast) and the Test Chart 2000 (at 100% and 10% contrast). Their statistical analysis revealed that both methods were very repeatable for both high and low contrast visual acuities and that the mean contrast visual acuity of both methods did not differ by more than one letter. This investigation[18] concluded that results from high and low contrast paper charts are directly comparable to computerised vision testing in terms of repeatability, accuracy and testing time.

Another type of chart that has been developed in this group is known as a mixed contrast chart. These mixed contrast charts uses reading instead of letter acuity and presents both high-contrast and low-contrast (10% for example) targets on the same side of the card. The high-contrast low-contrast difference, which is expressed in lines, is a measure of the slope of the Contrast Sensitivity Curve[19]. These charts (for example the Colenbrander and SKILL mixed contrast charts) were produced to make contrast testing less time consuming and to detect para-foveal losses (because reading involves a larger retinal area than letter recognition) which may precede foveal visual acuity loss.

Graphical representation of contrast sensitivity

1. Measurement of contrast sensitivity functions

Contrast sensitivity is defined as the reciprocal of contrast threshold and the variation of sensitivity over a range of spatial frequencies is illustrated in the Contrast Sensitivity Function (CSF) [2, 3]. That is, the graphical representation of sine-wave or periodic contrast sensitivity represents logarithmic contrast sensitivity as a function of variation in spatial frequency. It is generally plotted as an inverted U-shaped graph known as the CSF. Figure 4 illustrates a normal human CSF which peaks at 2.3 log contrast sensitivity (which is equivalent to a contrast sensitivity of about 200 and 0.5% contrast threshold) and spatial frequency between 2-6 cpd. A spatial frequency of 30 cpd is equivalent to 6/6 Snellen visual acuity. Such graphs can, however, be plotted using various scales other than a logarithmic one, that is, as percentage contrast thresholds, decimal contrast thresholds and directly using values for contrast sensitivity such as the 200 above. The CSF or curve has several distinct characteristics. Firstly, a band pass filter, which transmits frequencies within its band, and removes frequencies outside its band, indicating that of all the possible spatial frequencies only a select range is detected. Secondly, a low spatial frequency roll off which is defined as the gradual decrease in contrast sensitivity at spatial frequencies below the spatial frequency at which the peak contrast sensitivity occurs (usually between 2-6 cpd as in Figure 4). Lastly, a cut-off high spatial frequency (*x*-axis intercept or grating acuity limit) which is the highest spatial frequency that can be detected and in Figure 4 this frequency is at approximately 60 cpd. Contrast sensitivity varies between individuals and at approximately 20 years reaches a maximum (peak contrast sensitivity) between 2-5 cpd.

The degradation of contrast of an image in the optical subsystem is measured by MTF. The MTF measures how much the system attenuates spatial contrast and the curve describes the performance of the system for a range of spatial frequencies, namely fine and coarse patterns[21]. The MTF is defined[1] as the ratio of image contrast to object contrast as a function of spatial frequency and is measured by sine-wave gratings. A ratio of 1.0 for all spatial frequencies indicates that the optical system has produced a perfect image[1]. The degradation of contrast measured in the neural (retina and brain) subsystem is measured by the neural CSF[20-21]. Total CSF is measured with the various contrast sensitivity tests discussed earlier. The MTF and neural CSF are generally measured, with either one being measured and the other calculated. For example, the neural CSF was initially

measured with interference fringes or patterns (which theoretically allow a sinusoidal pattern to be formed directly on the retina) and MTF was then calculated from measured total CSF[22]. Campbell and Green[22] measured sinusoidal gratings formed on an oscilloscope to determine the total CSF. Thus, MTF was calculated by determining the ratios of the two over the range of spatial frequencies:

$$MTF = \frac{\text{CSF}}{\text{Neural CSF}} \quad (3)$$

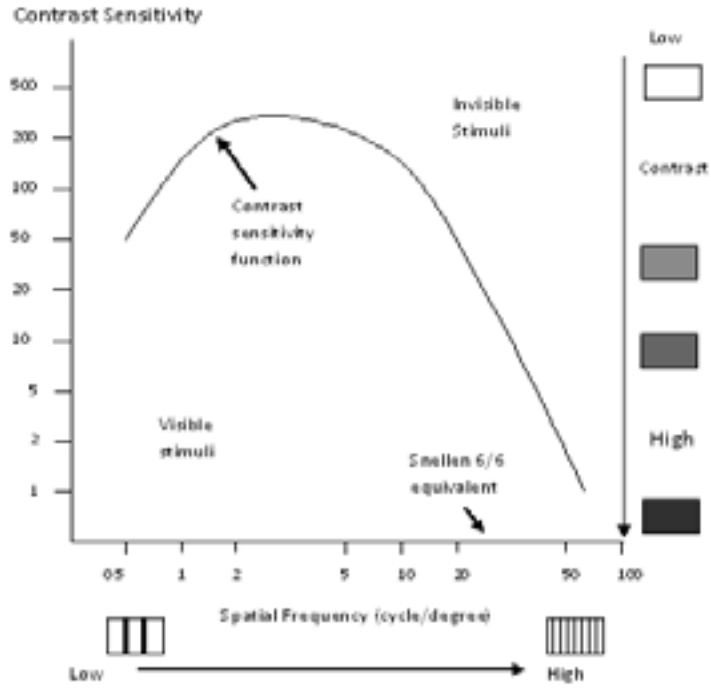

Figure 4. The contrast sensitivity function (CSF) is depicted by the inverted U-shaped curve; the boundary between seen and unseen gratings (or letters) is depicted by this curve. The figure has been adapted from Norton, Corliss, and Bailey[1].

The *normal* human CSF is the sum of the contrast sensitivity of the Modulation Transfer Function (MTF) and the neural CSF (neural CSF or NCSF) (Figure 5)[20-22]. Several neural and optical factors such as aberrations, diffraction, scatter, finite photoreceptor size, and noise in the neural pathways, as well as media transparency, accommodative state and pupil size, degrade contrast of an image formed on the retina[20].

Another method used by Whitaker and Elliot[23] to determine which factors (decreased optical quality, decreased neural function, or a combination of the two) decline visual function in older adults, was to simulate age-relate optical changes and examine their effects on younger observers. This included inducing pupillary miosis (by instilling a miotic), reducing stimulus luminance (to simulate increased absorption of the ocular media), and a scatter cell used to simulate light scatter. The total CSF was measured using the Pelli-Robson chart before and after optical simulation. Their results indicated that the presence of optical simulation produced no significant effect on visual performance and they thus concluded that under normal viewing conditions it was primary neural factors that underlie the deterioration in visual quality experienced in older observers. However, recently, with the availability of aberrometers (using various approaches such as the laser ray tracing or the double-pass method) wavefront data can be used to determine MTF[20].

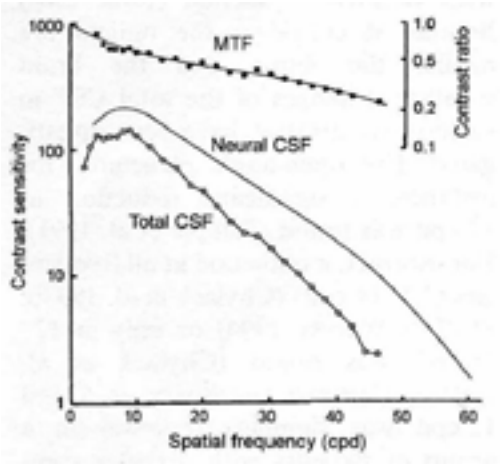

Figure 5. The calculation of Modulation Transfer Function (MTF) from measured Total Contrast Sensitivity Function (CSF) and measured Neural Contrast Sensitivity Function (Neural CSF) by Campbell and Green. Total CSF was measured using interference fringes and total CSF with sinusoidal gratings. MFT is calculated as the ratio of the two measurements[21] (Figure reproduced with permission from Micheal *et al*[20], 2011.)

Another more recent example of the relationship of these three functions is clearly illustrated in Micheal *et al*[20] where they calculated neural CSF from a conventionally measured total CSF (using CST 1800 and FACT charts) and a measured MTF (calculated from Zernike coefficients). In three groups of nine eyes (N=27 in total) containing eyes with normal ocular optics with mild diabetic retinopathy (altered retina), altered ocular optics with keratoconus (normal retina), and a normal control group. From Micheal *et al*, Figure 6 below depicts the mean and confidence intervals of the total CSF, MTF, and neural CSF of

the three groups. The control group displays normal patterns of the total CSF and MTF, with neural CSF higher then total CSF. In the retinopathy group, the neural CSF curves are all below the controls, and in the keratoconus group the MFT curves are well below the controls indicating neural and optical degradation of the visual subsystems respectively.

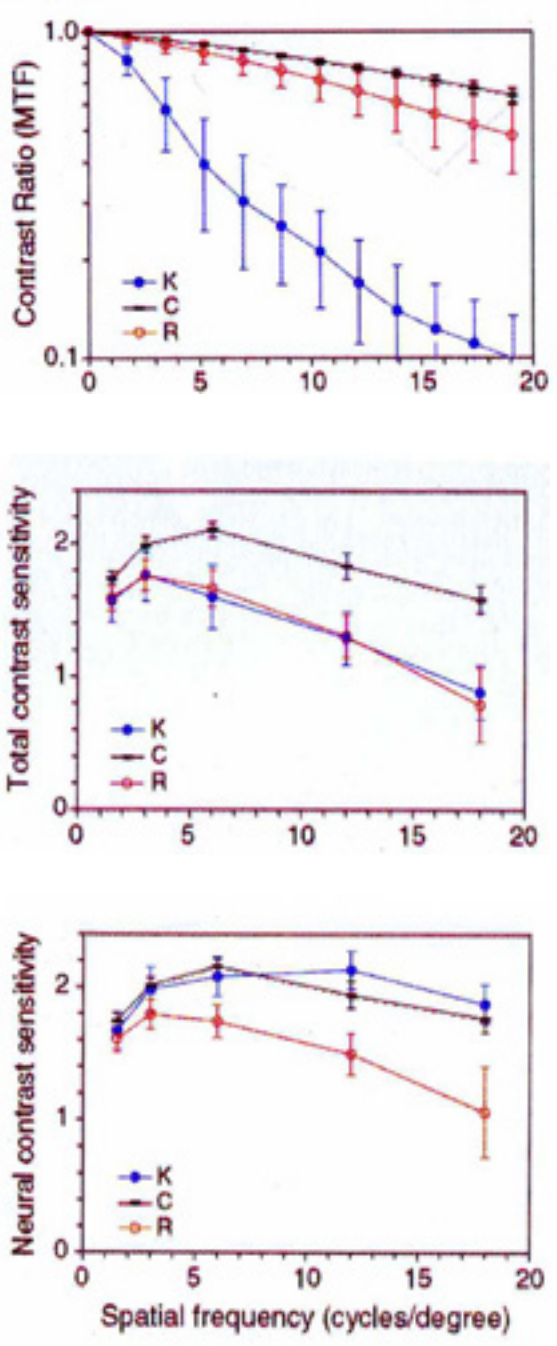

Figure 6. Mean and confidence intervals of Neural Contrast Sensitivity, Modulation Transfer Function and Total Contrast Sensitivity compared in three groups, controls (C) in black, diabetic retinopathy(R) in red, and keratoconus (K) in blue, in a study by Micheal *et al* [20].

2. *Contrast Sensitivity Curve (CSC)*

Graphical representation of non-periodic or letter charts measures contrast sensitivity as a function of visual acuity and produces curves known as CSC (Figure 7)[1, 8, 19, 24]. The relationship between these two measurements when plotted with visual acuity along the *x*-axis and contrast along the *y*-axis produces the CSC [1, 8, 19, 24]. Three types of test strategies can be used to determine the CSC[19, 24]. Firstly, when using contrast charts with fixed letter sizes and variable contrasts, the Pelli-Robson chart for example, analyses threshold contrast near the peak of the curve (point (a) in Figure 7). Secondly, charts which use different contrast (for example 50%, 10% and 2.5%) and different letter sizes can be used at both distance and near to determine threshold contrast visual acuities (in Figure 7, for example, point (b) for 10% contrast). Points located for 50% and 2.5% *et cetera* determine additional points on the curve. Lastly, the familiar high contrast letter acuity chart (point (c)) represents high-contrast threshold acuity[19, 24].

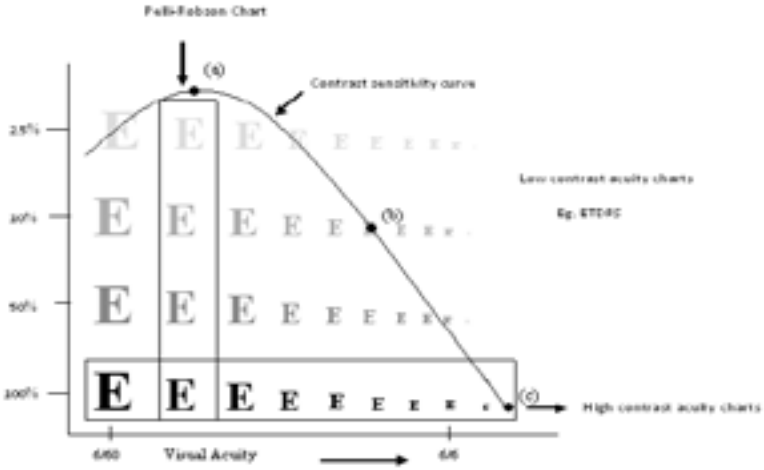

Figure 7. Contrast level (in percentage) is plotted on the vertical or *y*-axis against contrast visual acuity (CVA) on the horizontal axis. Only a single optotype, namely the letter "E" is shown on the graph. On the left side of the graph, 6/60 letters diminish in contrast from 100 to 25% (where the letter "E" becomes paler) whereas visual acuity diminishes in size along the horizontal or *x*-axis where the size of the letter decreases from 6/60 to 6/6. The boundary between seen and unseen letters is depicted by the curve, known as the contrast sensitivity curve (CSC). The declining right-hand slope of the CSC is measured mainly with medium and low contrast visual acuity charts which may indicate neuro-ophthalmological abnormalities in the early stage of disease such as diabetes mellitus and glaucoma. (Figure has been adapted from Norton, Corliss and Bailey[1]).

3. *Representation of contrast visual acuities in a vector space*

Contrast visual acuities were first represented in a 3-space in a study comparing contrast visual acuities in the right and left eyes of subjects with and without diabetic retinopathy (DR) and diabetic macular edema (DME)[25, 26] . The 3-space used to plot contrast visual acuities in diabetic subjects without DR (n=156) is represented in Figure 8. The origin here is $(0 \quad 0 \quad 0)'$ LogMAR which is equivalent to 6/6 visual acuity. The axes in Figure 8 could represent any (three) chosen contrast visual acuity levels (and, for example, here C100%, C10% and C2.5% were used). In eyes that can achieve better acuities such as 6/3, their contrast visual acuities would be plotted on the negative halves of the axes. A single dot represents results for an eye for the three chosen contrast levels; that is, a 3 × 1 vector $(C100 \quad C10 \quad C2.5)'$ LogMAR is plotted (MAR can also be plotted directly without the log transformation). Surfaces of constant probability density such as distribution ellipsoids and confidence ellipsoids also can be represented in this space; and in Figure 9 confidence ellipsoids are used to compare the differences in means between subjects with DR compared to subjects with DME. The shape, orientation and volume of the ellipsoids can also provide additional comparative information. Furthermore, other multivariate statistics or methods such as means, variances and co-variances and hypothesis tests can also be conducted on contrast visual acuities and there is the potential of possibly diagnosing and monitoring DR and DME[25-26] in this manner. The representation of contrast visual acuities in a 3-space has potential uses in many clinical and research studies involving the diagnosis, investigation or monitoring of various ocular and systemic diseases (with ocular manifestations) [25, 26]. However, normative demographic and age-related data is not yet readily available to easily make comparisons or identify deviation of results from norms (although the authors of this study are presently involved is establishing some preliminary findings towards this objective).

Conclusion

Contrast sensitivity tests are readily available, easy to use, and generally reliable[8-15]. The popularity of certain tests in clinical studies, such as the Pelli-Robson contrast test, is mainly based on good test-retest reliability and perhaps more importantly on the availability of published normative data[12]. Data available from a normal population forms the basis for comparing results. Thus, measurements deviating from the normal contrast measurements can be used for diagnosing and monitoring diseases or drug treatments[11, 25-28], investigating cataract and refractive surgery outcomes[10] and in different population studies used to determine acuity loss and functional vision[15]. Graphical representation of contrast visual acuities in a 3-space represents the relationship between any three specified levels of contrast visual acuities[25, 26].

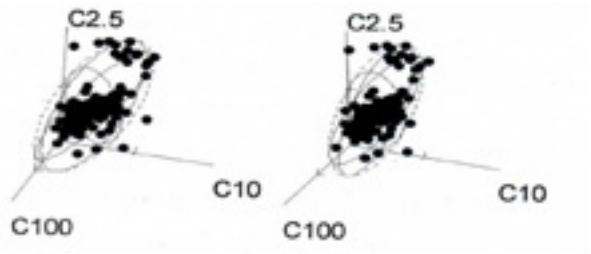

Figure 8. Stereo-pair scatter plots of contrast visual acuities at high, medium and low contrast levels (100%, 10% and 2.5% respectively) of diabetic patients without obvious diabetic retinopathy. A surface of constant probability density (or 95% distribution ellipsoid) is represented. The origin is 0 LogMAR or Snellen 6/6. Tick intervals are at 1 LogMAR or a change to 6/60 (or 0.1 in decimal notation). The edge of any axis is equal 2 LogMAR (or 6/600 or 0.01).

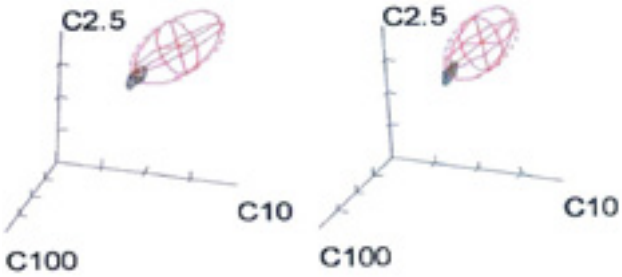

Figure 9. A comparison of surfaces of constant probability density (95% confidence ellipsoids) for contrast visual acuities for the eyes of diabetics[25, 26], firstly without DR and DME (black ellipsoid) and secondly with DME (red ellipsoid). The origin is $(0 \quad 0 \quad 0)'$ LogMAR and tick intervals of 0.25 LogMAR apply. Perhaps, not too unexpectedly, CVA was more variable and generally worse in the eyes with DME[25, 26]; that is, in comparison with the black ellipsoid the red ellipsoid has a greater volume and is shifted further away from the origin.

In many instances, raw data and the orientation, shape and volume of surfaces of constant probability density (ellipsoids) and corresponding variance-covariance matrices are easily comparable[25, 26] between samples. However, a limitation of the use of multivariate analysis on contrast visual acuities is that, firstly, there are no current published normative data for comparison and secondly, there is little known about short-term variation of inter- and intra-ocular contrast visual acuities. Research by the authors is on-going to address to some extent the abovementioned limitations and future results will provide some normative demographic and age-related data and also information concerning variability and test-retest reliability of contrast visual acuities.

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