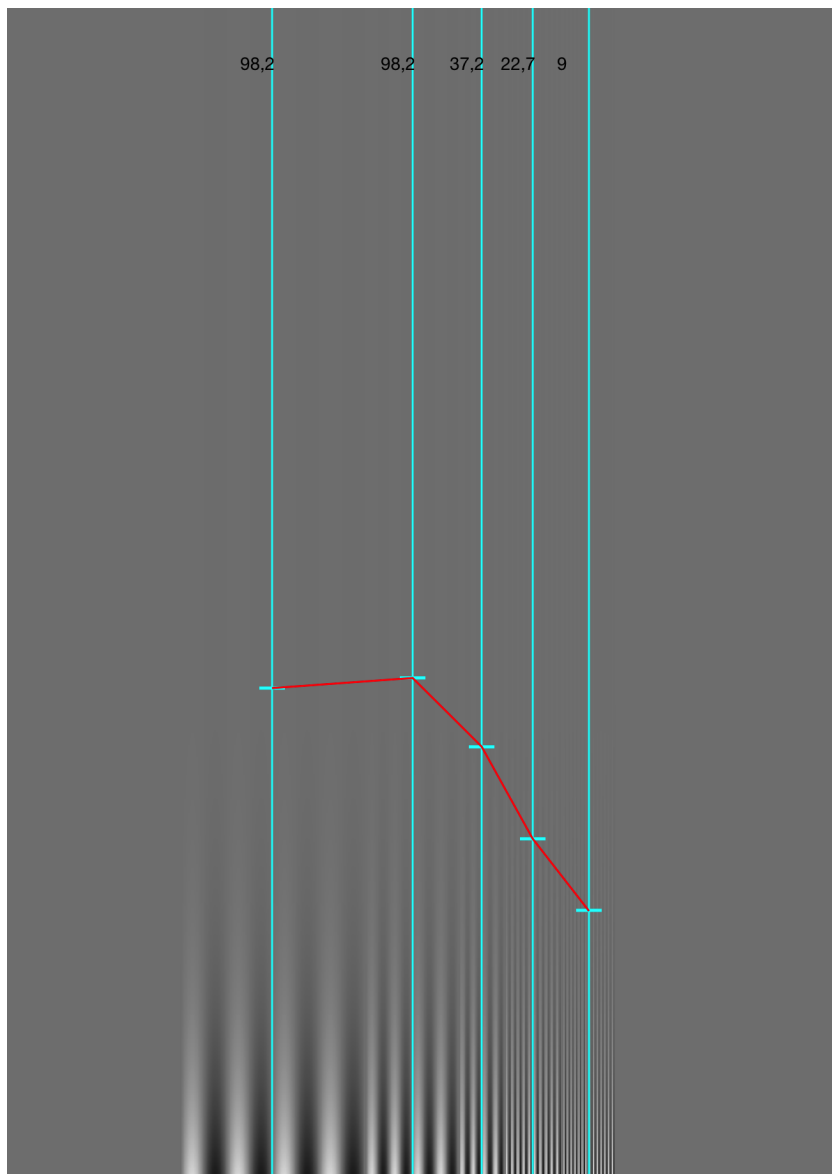




UPPSALA  
UNIVERSITET

# RapiCSF - A fast test of spectral contrast sensitivity

Lars Malmqvist





## Contents

<b>1</b>	<b>Introduction</b>	<b>5</b>
<b>2</b>	<b>Methods</b>	<b>6</b>
2.1	Subjects . . . . .	6
2.2	Equipment . . . . .	6
2.2.1	Hardware . . . . .	6
2.2.2	Software . . . . .	6
2.2.3	The prototype . . . . .	7
2.2.4	RapiCSF software . . . . .	7
2.2.5	Other software . . . . .	8
<b>3</b>	<b>Procedure</b>	<b>8</b>
3.1	Experimental design . . . . .	9
3.2	Statistical parameters . . . . .	9
3.3	CSF measurements . . . . .	9
<b>4</b>	<b>Results</b>	<b>10</b>
4.1	Analysis of sources of variation . . . . .	10
4.2	Examination time . . . . .	10
4.3	Area under the contrast sensitivity function . . . . .	11
<b>5</b>	<b>Discussion</b>	<b>11</b>
5.1	Hardware . . . . .	11
5.2	Software . . . . .	12
5.3	Procedure . . . . .	12
5.4	Variance estimates . . . . .	12
5.5	Examination time . . . . .	13
5.6	Area under the contrast sensitivity function . . . . .	13
5.7	Future . . . . .	13
	<b>References</b>	<b>14</b>
<b>A</b>	<b>Appendix</b>	<b>17</b>
A.1	Some words on A/D conversion . . . . .	17
A.2	On colour spaces, computer graphics and computer screens - brief remarks . . . . .	17



### Abstract

The contrast sensitivity function (CSF) and its variation over different spatial frequencies, is important for the overall visual performance of humans. Measurements of the CSF are common in research whenever a complete visual assessment is required. However its adaption into routine ophthalmological and optometric practice has been limited. This is due to the time it takes to perform a complete CSF-test. The here invented new computer based test is similar to the Gabor patches used in other CSF-tests, the difference being that it modulates frequency on the x-axis and contrast on the y-axis. This creates one test image with all contrast and frequency levels desired. The patient can then trace along the perceived visual outline of the image. The RapiCSF system was tested on a group of healthy volunteers and compared with the standard Vistech chart test. The mean time for one RapiCSF test was 13 s compared to 87 s for the Vistech chart. The difference of test time between the two tests was statistically significant. The RapiCSF test has the potential to measure contrast sensitivity in children and persons with cognitive impairment, considering its simplicity. Since the resolution limit of the retina equals the CSF at high contrast and high spatial frequencies, acuity testing with Snellen charts are redundant if CSF is tested with sufficiently high frequencies. The RapiCSF test can potentially replace acuity charts as well as current CSF tests.

### Sammanfattning

Kontrastkänslighetsfunktionen (CSF) hos det mänskliga ögat är, enkelt uttryckt, ögats och synsinnets förmåga att särskilja två närliggande ytor där ytorna har olika intensitet av ljusutstrålning. (luminansskillnader). Om ljusintensitetsskillnaden är tillräckligt liten kommer ögat att uppleva ytorna som lika ljusstarka. Ljusintensiteter som utstrålas från en yta kan beskrivas som en oändlig kombination av sinusvariationer av ljusintensitet. En skarp kant mellan vitt och svart byggs upp av höga spatialfrekvenser men en suddig kant saknar höga spatialfrekvenser. Spatialfrekvensen uttrycks oftast som variationer i luminans per bågminut. Förmågan att skilja små variationer i luminansen varierar med stimulits spatialfrekvensinnehåll.

Det mänskliga seendet beror av flera funktioner i en kedja. Sammantaget representeras dessa funktioner, inkluderande optisk avbildning i ögats optik, överföring av ljus till elektrisk impuls samt primär bildbehandling i näthinnan, informationsöverföring via synbanan till synbarken och integrering av syninformationen i frontalbarken, av det som kallas överföringsfunktionen (eng. Transfer Function, TF) hos synsinnets. Denna funktion beskriver hur väl den inkommande informationen, i detta fall ljus, överförs i ett informationsbärande system. Den optiska överföringsfunktionen (eng. OTF) är TF för en avbildning i ett optiskt system, t.ex. ögats optik. OTF definieras som optikens förmåga att överföra kontrast (luminansskillnader) genom systemet. Definitionen av kontrast vid mätning av OTF är den samma som vid mätning av CSF. TF består av de ingående överföringsfunktionerna i varje steg i bildöverföringen i synsinnets multiplicerade med varandra.

Det är idag möjligt att direkt mäta ljusbrytningen i ögats optik med hjälp av en aberrometer. Retina och efterföljande delar av synsystemet, går ännu inte att mäta direkt. Klinisk används syntavlor som indirekta



mått på synsinnets TF. Problemet med syntavlor är att de endast mäter en del av TF - nämligen förmågan att överföra information med medel/höga spatialfrekvenser vid hög kontrast. Vilket är en begränsad del av TF för synsinnet. CSF är TF för synsinnet vid ett givet antal spatialfrekvenser. Hur detaljerad bilden av synsinnets TF blir, beror på hur många spatialfrekvenser man testat i det specifika CSF-testet.

Varför används då inte kontrastkänslighetstestning rutinmässigt hos optiker och ögonläkare? Kruxet är att många CSF-tester är krångliga och tar lång tid, framförallt om man vill undersöka många spatialfrekvenser. Traditionellt används så kallade Gabor-fläckar för testning av CSF. Gaborfläckar är cirkulära bilder med ljusintensitet som varierar som en sinusfunktion. En kontrastnivå och en spatialfrekvens testas per Gaborfläck. Andra test offerar specificitet genom att testa approximativa frekvensområden i syntavlor med varierande kontrast. Tyvärr får man då inte svar på exakt vilka spatialfrekvenser man undersöker.

CSF är ett specifikt mått på felbrytning och ljusspridning ögats optik. Däremot har inte CSF hög sensitivitet eller specificitet för sjukdomar i andra delar av ögat. Därför kan det endast användas som ett komplement till anamnes och ögonundersökning. I praktiken har CSF-mätning förblivit en undersökningsmetod som huvudsakligen används i forskningssammanhang.

RapiCSF består av en bild genererad av en dator och presenterad på en bildskärm. Kontrasten i bilden varierar i Y-led och spatialfrekvensen i X-led. Försökspersonen upplever en bild av de spatialfrekvenser och kontrastnivåer som synsinnet kan upplösa och markerar mellan bilden och bakgrunden. Koordinaterna för gränslinjen identifieras och omvandlas till kontrastvärden av mjukvara som presenterar gränslinjen på skärmen. Tidsåtgången för att testa ett öga med RapiCSF var i genomsnitt 13 sekunder jämfört med 87 sekunder för Vistechmetoden, som valdes som referens. Skillnaden var statistisk säkerställd mellan de två grupperna. Variationen mellan individer var densamma för mätmetoderna. Däremot var variationen för mätningar inom individ mindre med RapiCSF än med Vistechtavla.



## 1 Introduction

The signal transduction through the eye and to the retina is dependent on the Optical Transfer Function (OTF) of the optics of the eye, i.e its ability to convey contrast differences from the source image to the retina. The OTF is influenced by the wavelength of the light, pupil diameter, refractive error, optical aberrations, diffraction and light scattering. Theoretical models and empirical data for the OTF of the eye has been described in the literature.<sup>1,2</sup> In the 1960's, research concerning the importance of spatial content in visual stimuli, applying Fourier-analysis to the results of contrast threshold experiments, was published. This early research hypothesised that the visual system has specific channels for different spatial frequencies.<sup>3</sup> This hypothesis spurred interest in further research. In my opinion that research can be roughly divided into four areas:

1. The fundamental understanding of the visual system.
2. The characterisation of the CSF in persons with disease affecting the eye and visual pathway.
3. The association between the CSF and specific tasks such as piloting an aeroplane or driving a car at night.
4. The development of technical equipment or methods in the broadcasting, computer and medical imaging industries, respectively.

The evidence for the variable sensitivity for different spatial content in visual stimuli has been well established in cats, humans and other primates.<sup>4,5,6</sup>

For the past 40 years a number of methods have been developed for the measurement of the CSF. Some tests have been developed for particular research projects.<sup>7,8,9,10,3</sup> Other tests have become standard and are used extensively in research. Examples include tests developed by Ginsburg,<sup>11</sup> Bach,<sup>12</sup> Pelli et al,<sup>13</sup> Arden and Jacobson.<sup>14</sup> They all have citation counts between 200 to over 800 in Google Scholar. These four test are of two types. Either they consist of identifying gratings that the test subject selects according to some forced-choice algorithm (Ginsburg and Arden test), or identification of letters/symbols in conventional optotype-charts with decreasing contrast (Bach and Pelli).

Visual acuity is a subjective indirect measurement of the highest spatial frequency the visual system can transfer, at high contrast. The overall performance of an optical system is determined by its OTF. The OTF and the CSF are the same in a system where the stimuli satisfies the requirements for the use of Michelson contrast.<sup>15,16,17</sup> However, the OTF covers any and all spatial content, while the CSF is usually measured for only a limited number of frequencies. A CSF measurement can replace acuity if measured at sufficiently high frequencies. The visual acuity corresponds to the spatial frequency where the subject contrast threshold approaches 1.

Contrast sensitivity measurements are routine in ophthalmological research when a complete assessment of visual function is desired. Changes in the CSF has been used in research to asses the severity of cataracts, the effect on visual performance induced by different types of IOLs and the outcome of refractive



surgery<sup>18,19,20,21</sup> Measurements of the CSF has also been used in the quantification of vision loss that isn't caused by optical defects. Examples include MS, glaucoma and macular degeneration.<sup>22,23,24</sup>

CSF is specific test for diffraction, aberration and light scattering in the eye. Unfortunately no specific ocular or other disease is associated with only a loss of contrast vision without or with negligible loss of acuity. Current CSF-testing is time consuming. Therefore, CSF testing, if done in a routine clinical setting at all, is relegated to a role as a back-up test when a patient has normal or near normal acuity while still complaining about vision loss.<sup>25</sup> Despite the fact that it provides a more complete assessment of vision.

However if a CSF test was quick and easy to administer, and included high spatial frequencies for assessment of acuity, it could become an important tool in the clinic. The goal of this project was to create a method that allows quick measurement of the CSF, to compare the test time with that of a standard CSF-test and evaluate the relative precision of both tests.

## 2 Methods

### 2.1 Subjects

Healthy volunteers (n = 20) where recruited from medical students at Uppsala University Hospital and staff at the Ophthalmological clinic. Written informed consent was obtained from each subject. Ethical approval, from an IRB, was not required for this project according to Swedish law.

### 2.2 Equipment

#### 2.2.1 Hardware

An iPad using a HDMI-output adapter was connected to an 24" TFT-screen (NEC PA241W, NEC Display Corp, 2012) using a 7,5 m HDMI-to-DVI cable. The display was calibrated using a colourimeter (1Display Pro, X-Rite Corp, 2012) of the same make and model as the one usually shipped with the screen. A separate light meter was used to measure illuminance in parallel with measurement of illuminance with the light-meter in the colourimeter.

#### 2.2.2 Software

The software consists an image generator and a user interface. Some of the parameters considered during the development of the software:

- Angular size of test image in the viewers FOV (field-of-view)
- Angular size of each spatial frequency
- Decrease of contrast as a function of the X-axis
- Size of screen in pixels and millimetres
- Average luminance of the screen
- Angular resolution of the eye



Based on these parameter, a prototype software was developed with MATLAB (MATLAB R2012B, Mathworks, USA) on a personal computer.

### 2.2.3 The prototype

The prototype uses a number of input values - screen dimensions in pixels, dot pitch in mm, distance between screen and research subject, the spatial frequencies to test, number of periods per frequency and an empirical constant to decrease the contrast towards 0. A vector is created for each spatial frequency according to (1), where the granularity is set according to the number of pixels required to create a suitable FOV. These vectors are merged into one, creating the X-axis of the test image. A sine function is applied to each element of the vector and the results stored in a new vector. This vector is stacked vertically to form a matrix while the contrast on each row is continuously modulated (2). Each row is multiplied with an empirical factor (3), to decrease contrast according to its position on the Y-axis. The contrast for each row can then be calculated using the formula for the Michelson contrast (4), since the maximum and minimum luminance levels are proportional to the rows position on the vertical axis and the empirical factor.

$$V = -n\pi \dots n\pi, n = \text{number of periods} \quad (1)$$

$$R_2 \leftarrow R_1 (127,5 + E \times (127,5 \times \beta^n)), E = \text{every element in row } R_1 \quad (2)$$

$$\beta^n, n = \text{pixels on } Y - \text{axis of screen} \quad (3)$$

$$\text{Contrast} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}, I_{max} \text{ and } I_{min} \text{ being the highest and lowest luminance respectively} \quad (4)$$

### 2.2.4 RapiCSF software

The prototype described above was implemented in Objective-C on an iPad running iOS 6.1.1 using a development environment (Xcode, Apple Inc. 2013) The software uses the following input parameters:

1. Dimensions, in pixels, of the output screen.
2. Dot pitch of the output screen in millimetres per pixel and assuming square pixels.
3. An array of spatial frequencies to be tested.
4. An empirical constant, affecting the speed of the contrast gradient.
5. Minimum number of periods per spatial frequency
6. Minimum field of view per spatial frequency



7. Calibration file containing absolute luminance values for each digital drive level (DDL) or pixel value

The generated image can be displayed on either an iPads built-in screen or an external screen (Figure 1). To measure spectral contrast sensitivity in the case where the iPad displays the image directly, the test subject simply moves a finger along the borders of the generated image. This is possible because the figure formed by the different frequencies merge with the background at the individuals own contrast threshold. When an external screen is used the methods are the same. Except that the X-Y coordinates are transferred and corrected for aspect ration and resolution, to a highly visible circle on the external screen that moves with the finger.

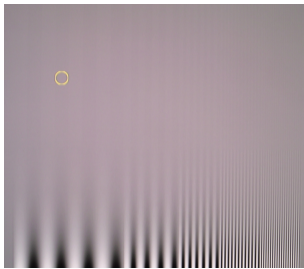


Figure 1: Image showing increasing spatial frequencies and decreasing contrast, generated by RapiCSF, as seen by the testee

To be precise, the X-Y coordinates are recorded and then matched to the contrast level at that point as given by (3) and (2) using the calibration data for the screen. (Figure 2)

### 2.2.5 Other software

The display manufacturer's calibration software (SpectraView II, NEC Display Corporation of America, 2013) was used due to the fact that it generates display profiles that are uploaded to the screen. Usually display calibration and profiling creates profiles that the computer, driving the display, loads into memory and run on its graphic card. iPads can't be

colour-calibrated. Therefore, colour-calibration necessitated a display with on-board calibration ability. To verify the calibration and to measure the luminance corresponding to each digital drive value (DDL) or pixel value, the author used an open source colour calibration package (ArgyllCMS, Graeme Gill, 2013) combined with correction files for the TFT-screen (created by the colourimeter manufacturer) and information regarding the chosen standard observer. This information is stored in the RapidCSF software calibration file, that contains measurements of absolute luminance for each DDL.

## 3 Procedure

The RapiCSF system and the Vistech 6500 chart<sup>11</sup> was placed in a spare room at the Ophthalmology clinic at Uppsala University Hospital. Room illumination was measured using an incident light meter and a colourimeter with a light diffuser. The measured illuminance varied between 100 and 500 lux and was within 15 lux of each other. Room lighting wasn't optimal for either test. The room was lit unevenly and too brightly to make the RapiCSF test conditions comparable to previous computer based test systems. An additional lamp had to be used for the Vistech chart to bring its illuminance to the required minimum



of 300 lux at all four corners. The chart was placed 10 feet from the test subject in accordance with the manufacturers suggestions.

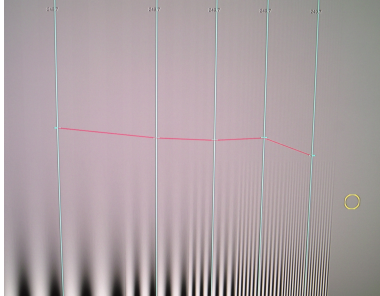


Figure 2: RapiCSF interface after measurements were taken, as seen by the test subject. The horizontal line in the middle is the CSF-curve for the test subject.

system where set to measure the same spatial frequencies as the Vistech chart, to facilitate a comparison (1.5, 3, 6, 12 and 18 cycles per degree). The empirical constant was set at 0.99, after a number of pre-study trials, to optimise the contrast gradient for the screen.

### 3.1 Experimental design

Altogether 20 subjects, 12 female and 8 male, were randomly distributed on two test method groups, RapiCSF or Vistech, containing an equal number of males and females. Each subject was measured twice, considering examination time and estimated area under the contrast sensitivity curve.

### 3.2 Statistical parameters

The significance level and confidence coefficient was set to 0.05 and 0.95, respectively, considering sample size and expected differences between test groups.

### 3.3 CSF measurements

Written informed consent was obtained and the subjects where then consecutively randomised to have their contrast sensitivity measured with either the RapiCSF system or the Vistech chart. Mono-ocular letter acuity was measured for both eyes with a Snellen letter chart. The subjects were always wearing their own glasses or contact lenses, if corrected. Only subjects with an acuity of at least  $\log\text{MAR} = 0$  where included ( $n = 20$ ). The subjects contrast sensitivity was measured mono-ocularly. Examination time and contrast sensitivity was recorded for each eye in all subjects. The second eye was measured immediately after the first. Each subject except one was tested during the same day.

AUC for each CSF curve was calculated using the trapezoidal rule (5). The time to perform a test was calculated as the mean of the test time for both



eyes. The mean of the AUC for both eyes was calculated as well. A T-test was performed on the calculated means for both time and AUC between groups.

$$\int_a^b f(x)dx \approx (b - a) \frac{f(a) + f(b)}{2} \quad (5)$$

## 4 Results

### 4.1 Analysis of sources of variation

The estimations of examination time and area under the contrast sensitivity function, respectively were analysed with an analysis of variance base on the the following model (6).

$$x_{ij} = \mu + A_i + \varepsilon_{j(i)} \quad (6)$$

An estimate,  $x_{ij}$ , can be assumed to be the sum of the population mean,  $\mu$ , a term for the variation among individuals,  $A_i$  ( $i = 1 \dots 10$ ) and a term for the variation among eyes within individual including the measurement error,  $\varepsilon_{j(i)}$  ( $j = 1, 2, 3$ ). The variances estimated for area under the contrast sensitivity function are given in (Table 1).

Table 1: Area under the contrast sensitivity function

Method	Sources of variation Individuals ( $rel^2$ )	Eyes and measurement error ( $rel^2$ )
Vistech	188836	46050
RapiCSF	110107	10352

The variance for eyes and measurement error for the Vistech strategy exceeded that of the RapiCSF ( $F - statistic = 4.44, F_{10;10;0.95} = 2.98$ ). Further, the variance for individuals measured with the Vistech strategy appeared to to exceed the variance for individuals measured with the RapiCSF (Table 1).

### 4.2 Examination time

The estimated examination time with the Vistech and the RapiCSF strategies, respectively is presented in (Table 2). The Vistech approach consumed more

Table 2: Examination time consumed per eye, Vistech and RapiCSF respectively

Strategy	Estimated 95 % confidence interval for the mean* (s)	
Vistech	87.2	$\pm 26.5$
RapiCSF	13.4	$\pm 3.8$

\*Degrees of freedom = 9

examination time than the RapiCSF method as evaluated from a 95 % confidence interval for the difference between the two strategies, [47;106] (d.f. = 18). Before the confidence interval was estimated, the approximation of the variances as equal was tested for with an F-test that was rejected ( $F - statistic = 48.45; F_{9;9;0.95} = 3.18$ ).



### 4.3 Area under the contrast sensitivity function

The contrast sensitivity recordings were slightly higher for the Vistech than for the RapiCSF, mainly for mid spatial frequencies (Figure 3).

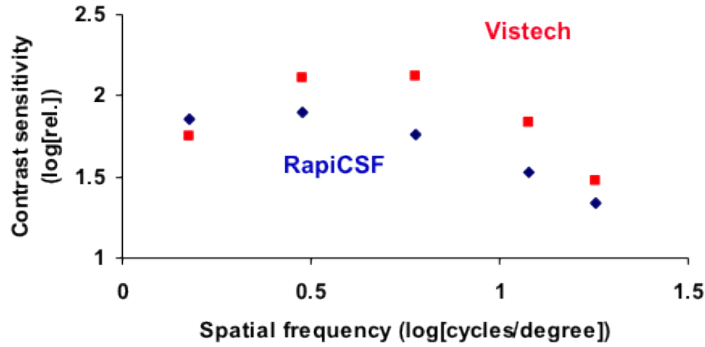


Figure 3: Spectral contrast sensitivity measured with Vistech and RapiCSF

The estimated area under the CSF-curve with the Vistech and the RapiCSF method, is presented in (Table 3). There was a difference between the Vistech

Table 3: Area under the contrast sensitivity function

Strategy	Estimated 95 % confidence interval for the mean* (Rel)	
Vistech	1419	±329
RapiCSF	757	±243

\*Degrees of freedom = 9

method and the RapiCSF method evaluated from a 95 % confidence interval for the difference between the two methods, [282;1042] (rel.) (d.f. = 9). Before the confidence interval was estimated, the approximation of the variances as equal was tested for with an F-test ( $F - statistic = 1.84$ ;  $F_{9;9;0.95} = 3.18$ ).

## 5 Discussion

The current project aimed to develop a new method for measurement of the contrast sensitivity function of human vision. Further, it was intended to compare the newly developed strategy with the current clinical standard. The current population was limited in age interval. It is possible that the variation and the levels would have changed if a population with a wider age interval had been defined.

### 5.1 Hardware

The monitor size was chosen to provide a visual field that corresponds to the macular visual field at a distance of approximately 5 m. The selected mon-



itor had to provide a high degree of control over contrast dynamics over wide luminance range and to enable research using a 10-bit imaging pipeline.<sup>26</sup>

## 5.2 Software

The software was designed so that the generated target should provide a minimum field of view for each special frequency to be measured, as well as a minimum number of periods.

## 5.3 Procedure

Interestingly enough, while this test is calibrated with absolute luminance values, no such calibration is undertaken for the Vistech chart. Without measurements of reflected light with a calibrated spectrophotometer, it's impossible to exactly know how high or low the actual contrast is. Especially since the manufacturer gives a fairly broad spectrum of lighting requirements for the chart.<sup>11</sup> This lack of calibration of the Vistech chart, combined with the variable and sub-optimal lightning conditions, has probably lowered the subjects contrast threshold. Combined with the fact that in the current study the subjects were wearing optical corrective glasses. It is anticipated that eyeglasses generally decreases the contrast vision. In the present study both eyes were measured once. In order to separate the variation between eyes and among measurements it would have been preferable to iterate measurements within an eye. This will be considered in future studies.

## Results

### 5.4 Variance estimates

The finding that the variance for individuals with both strategies exceed the variance for eyes and measurement error (Table 1) indicate that for comparison of explanatory variables associated with the contrast sensitivity function, it is more efficient to include a large number of individuals than to average many measurements within each individual. Another approach would be to use a cross over design to avoid the variation among individuals.

The observation that variation between the eyes with the RapiCSF approach was lower than with the Vistech chart. (Table 1) indicates that the RapiCSF is associated with higher precision. However, it cannot be judged if the difference in precision is associated with variability between eyes or measurements due to the experimental design. Also, it cannot be excluded that the better precision is a consequence of a lower dynamic range. This could be evaluated in the future by fitting known noise filters on subjects.

It should be noted that supra-threshold measurements where observed for some subjects. It was certainly caused by the decision to use the centre of the pointer as the reference for coordinate measurement. When the subjects moved the cursor along the outline of the figure at their threshold, the centre of the cursor was in supra-threshold territory. Those data points where changed to the adjacent lower value, i.e the closest non-supra threshold contrast value. Using this uncorrected data the mean of the AUC for RapiCSF rose to 1136 and the difference between the tests wasn't significant. Further development of



the RapiCSF system is under way to correct the design flaw that caused the presumed error

### **5.5 Examination time**

The finding that the examination time with the RapiCSF strategy was far shorter than with the Vistech strategy (Table 2) strongly demonstrates the potential of the RapiCSF strategy for routine clinical use.

### **5.6 Area under the contrast sensitivity function**

The current finding that the absolute level of area under the contrast sensitivity function was lower (Table 3) with the RapiCSF could be caused by a lower dynamic range. Future versions of this test should operate on a 10-bit graphics platform, to enable low absolute differences between grey levels, without resorting to low luminance and gamma curve manipulation tricks.

### **5.7 Future**

A recent study<sup>10</sup> used an eye-tracker and a computer, showing a film while modulating the spatial frequency content around the area where the subject was looking, asking the subjects to push a button if they detected any change in the image. This rendered much worse contrast sensitivity figures than in previous studies. Despite the fact that it - compared to this, and other experiments was more life-like. Hence the jury is still out on how one best should measure the CSF. Further studies are needed.



## References

- [1] van Meeteren A. Calculations on the Optical Modulation Transfer Function of the Human Eye for White Light. *Optica Acta: International Journal of Optics*. 1974;21(5):395–412. Available from: <http://www.tandfonline.com/doi/abs/10.1080/713818902>.
- [2] Campbell FW, Gubisch RW. Optical quality of the human eye. *The Journal of Physiology*. 1966 Jan;186(3):558–578. Available from: <http://jp.physoc.org/content/186/3/558>.
- [3] Campbell FW, Robson JG. Application of fourier analysis to the visibility of gratings. *The Journal of Physiology*. 1968 Jan;197(3):551–566. Available from: <http://jp.physoc.org/content/197/3/551>.
- [4] Maffei L, Fiorentini A. The visual cortex as a spatial frequency analyser. *Vision research*. 1973;13(7):1255–1267. Available from: <http://www.sciencedirect.com/science/article/pii/0042698973902010>.
- [5] Blakemore C, Campbell FW. On the existence of neurones in the human visual system selectively sensitive to the orientation and size of retinal images. *The Journal of Physiology*. 1969 Jan;203(1):237–260. Available from: <http://jp.physoc.org/content/203/1/237>.
- [6] Rolls E, Baylis G, Leonard C. Role of low and high spatial frequencies in the face-selective responses of neurons in the cortex in the superior temporal sulcus in the monkey. *Vision Research*. 1985;25(8):1021–1035. Available from: <http://www.sciencedirect.com/science/article/pii/0042698985900914>.
- [7] Owsley C, Sekuler R, Siemsen D. Contrast sensitivity throughout adulthood. *Vision Research*. 1983;23(7):689–699. Available from: <http://www.sciencedirect.com/science/article/pii/0042698983902109>.
- [8] Owsley C, Sloane ME. Contrast sensitivity, acuity, and the perception of 'real-world' targets. *British Journal of Ophthalmology*. 1987 Jan;71(10):791–796. Available from: <http://bjo.bmj.com/content/71/10/791>.
- [9] Kitaguchi S, MacDonald L, Westland S. Evaluating contrast sensitivity. *Human Vision and Electronic Imaging XI, Proc of SPIE-IS&T Electronic Imaging*. 2006 Feb;6057:605704–605704. Available from: <http://dx.doi.org/10.1117/12.643188>.
- [10] Dorr M, Bex PJ. A gaze-contingent display to study contrast sensitivity under natural viewing conditions. In: *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*. vol. 7865; 2011. p. 32. Available from: [http://scholar.harvard.edu/mdorr/files/dobe11\\_www.pdf](http://scholar.harvard.edu/mdorr/files/dobe11_www.pdf).
- [11] Ginsburg A. A new contrast sensitivity vision test chart. *American journal of optometry and physiological optics*. 1984 Jun;61(6):403–407. Available from: <http://ukpmc.ac.uk/abstract/MED/6742102>.



- [12] Bach M. The Freiburg Visual Acuity test—automatic measurement of visual acuity. *Optometry and vision science: official publication of the American Academy of Optometry*. 1996 Jan;73(1):49–53. PMID: 8867682.
- [13] Pelli D, Robson J, Wilkins A. The design of a new letter chart for measuring contrast sensitivity. *Clin Vis Sci*. 1988;2(3):187–199.
- [14] Arden GB, Jacobson JJ. A simple grating test for contrast sensitivity: preliminary results indicate value in screening for glaucoma. *Investigative Ophthalmology & Visual Science*. 1978 Jan;17(1):23–32. Available from: <http://www.iovs.org/content/17/1/23>.
- [15] Williams CS, Becklund OA. *Introduction to the Optical Transfer Function*. SPIE Press; 1989.
- [16] Peli E. Contrast in complex images. *Journal of the Optical Society of America A*. 1990 Oct;7(10):2032–2040. Available from: <http://josaa.osa.org/abstract.cfm?URI=josaa-7-10-2032>.
- [17] Michelson AA. *Studies in Optics*. Courier Dover Publications; 1927.
- [18] Koch D. Glare and contrast sensitivity testing in cataract patients. *Journal of cataract and refractive surgery*. 1989 Mar;15(2):158–164. Available from: <http://ukpmc.ac.uk/abstract/MED/2724116>.
- [19] Friström B, Lundh BL. Colour contrast sensitivity in cataract and pseudophakia. *Acta Ophthalmologica Scandinavica*. 2000;78(5):506–511. Available from: <http://onlinelibrary.wiley.com/doi/10.1034/j.1600-0420.2000.078005506.x/abstract>.
- [20] Rodríguez-Galietero A, Montés-Micó R, Muñoz G, Albarrán-Diego C. Comparison of contrast sensitivity and color discrimination after clear and yellow intraocular lens implantation. *Journal of Cataract & Refractive Surgery*. 2005 Sep;31(9):1736–1740. Available from: <http://www.sciencedirect.com/science/article/pii/S0886335005004268>.
- [21] Superstein R, Boyaner D, Overbury O. Functional complaints, visual acuity, spatial contrast sensitivity, and glare disability in preoperative and post-operative cataract patients. *Journal of Cataract & Refractive Surgery*. 1999 Apr;25(4):575–581. Available from: <http://www.sciencedirect.com/science/article/pii/S0886335099800595>.
- [22] Lennerstrand G, Ahlström CO. Contrast sensitivity in macular degeneration and the relation to subjective visual impairment. *Acta Ophthalmologica*. 1989;67(3):225–233. Available from: <http://onlinelibrary.wiley.com/doi/10.1111/j.1755-3768.1989.tb01863.x/abstract>.
- [23] M W, A A, I BW. Contrast sensitivity in retinal disease. *Ophthalmology*. 1980 Nov;87(11):1140–1149. Available from: <http://europepmc.org/abstract/MED/7243206>.
- [24] Skalka HW. Comparison of Snellen acuity, VER acuity, and Arden grating scores in macular and optic nerve diseases. *The British*



- Journal of Ophthalmology. 1980 Jan;64(1):24–29. PMID: 7356929 PMCID: PMC1039342. Available from: <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1039342/>.
- [25] Moseley MJ, Hill AR. Contrast sensitivity testing in clinical practice. *British journal of ophthalmology*. 1994;78(10):795–797. Available from: <http://bjo.bmj.com/content/78/10/795.short>.
- [26] Fetterly KA, Blume HR, Flynn MJ, Samei E. Introduction to Grayscale Calibration and Related Aspects of Medical Imaging Grade Liquid Crystal Displays. *Journal of Digital Imaging*. 2008 Jun;21(2):193–207. PMID: 17333412 PMCID: PMC3043865. Available from: <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3043865/>.
- [27] Kimpe T, Tuytschaever T. Increasing the Number of Gray Shades in Medical Display Systems—How Much is Enough? *Journal of Digital Imaging*. 2007 Dec;20(4):422–432. PMID: 17195900 PMCID: PMC3043920. Available from: <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3043920/>.





## A Appendix

### A.1 Some words on A/D conversion

Computers and other binary devices inherently describes everything with 0's and 1's. This is important when one wishes to convert an analog signal, light or sound, to digital information. To aid ourselves in this effort we've developed analogue to digital converters (A/D). They convert an analogue curve of changing voltage, amperage etc. to digital data. This conversion is dependent on many factors, one of them is the bit-depth of every sample. If one uses many bits to describe a curve, the accuracy of the digital description increases. In the case of sound - the digital recording with a higher bit-depth will sound better when converted back to analogue sound in a stereo system. A CD uses 16-bits per sample, giving  $2^{16} = 65536$  levels of sound. The bit-depth is also called dynamic range.

### A.2 On colour spaces, computer graphics and computer screens - brief remarks

Computers usually handle colour information in a RGB colour space where red, green and blue are the primary colours in an additive (emissive) space. Hence the colour white equals the maximum value of each of the three primary colours. Black is described as the minimum value of the colours. In printing the CMYK colour space is used. CMYK is a subtractive (reflective) space. Meaning that maximum values of CMYK creates the colour black since the least amount of light is reflected. Computers handle colour information with differing precision (could also be called bit-depth or dynamic range). Digital cameras usually have between 8-14 bits of data per colour channel i.e 24-42 bits per pixel. Digital X-ray machines typically have 16 bits of dynamic range, but they're achromatic/monochromatic since the machines only measure one "colour", the absorption of X-rays in tissue.

Computer monitors, i.e LCD- CRT- and Plasma-monitors commonly have 6-8 bits per channel in dynamic range. That gives  $2^8 \times 2^8 \times 2^8 = 16777216$  different colours. If you're only interested in luminance differences, then the maximum number of grey levels an 8-bit monitor can show are  $2^8 = 256$ . Research has shown that healthy humans under good conditions have  $\approx 9$  to 10 bits of dynamic range. That equals  $2^9 \dots 2^{10} = 512 \dots 1024$  shades of grey.<sup>27</sup> How does radiology solve this conundrum - 16 bit data, 8 bit monitors and 10 bit humans?

By utilising mapping tools radiologists can move data in the 16-bit space and map it to their own 10 bit space. Display manufacturers use tricks such as temporal and spatial dithering to increase their screens dynamic range to 10-12 bits.

Temporal dithering is accomplished using the rapid cycling between two colours to create the appearance of a third. Spatial dithering can be performed by downscaling the monitor resolution or by sub-pixel addressing. In the first case, the screen loses resolution. In the second case the screen risk losing colour fidelity on the individual pixel level. The conclusion drawn is that a computer system utilising only 8 bits luminance data can't measure the maximum contrast sensitivity under ideal circumstances. However to achieve the 10 bits of dynamic range that humans have, the luminance has to be fairly high. In the DICOM



GSDF standard screens are commonly set at maximum output luminance, up to  $600 \text{ cd/m}^2$ , combined with gamma settings that maximises the contrast between each digital drive level (input luminance value).<sup>26</sup> Thus a system that isn't configured for maximum discrimination could - in theory, resolve the contrast threshold of humans even if it has less than 10 bits of dynamic range. A hypothetical system satisfying that requirement would have most of its DDL delta around the contrast threshold for a given spatial frequency. I. e having narrowly spaced luminance steps where the contrast threshold falls, and less narrow were it won't fall.