Master in Photonics

MASTER THESIS WORK

Exploring the relationship between Visual Acuity and Contrast threshold through defocus

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Exploring the relationship between Visual Acuity and Contrast threshold through defocus.

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Abstract. In optometry and more generally in vision research, the measure of visual acuity (VA) is the most extended way to evaluate and obtain psychophysical information about the quality of the vision. VA is a measure of the eye's resolution and it is related to the Contrast Sensitivity Function (CSF), that is obtained using a grating with different spatial frequencies and different contrasts. In this master thesis we explored the possibility to relate VA (only the size of the stimuli is changed) with the Contrast Sensitivity (CS) threshold at a spatial frequency of 18cycles/degree (c/d) (only the contrast is changed) through spherical defocus. To explore the possible correlations, we measured both VA and CS to 20 subjects with six different levels of spherical defocus, i.e., from 0.00 D (diopters) to 1.25 D (0.25D-step). The results showed significant correlations (rho spearman >= 0.50 in all cases) between VA and CS for each level of defocus. These correlations suggested a potential important application to overcome the current limited resolution in virtual reality displays.

Keywords: Contrast Sensitivity (CS), Visual Acuity (VA), Defocus, QUEST.

1. Introduction

The minimum angle of resolution (MAR) of an optical system can be defined as the minimum angle between two distinguishable entities.[1] 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. The VA is a measure of the ability of the visual system to detect, recognize or resolve spatial detail in a high-contrast tests and a good level of lighting.[2]

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. It is important to have in mind in this study that when and optotype is shown in a computer display it is recommended to use 5 pixels for each stroke[3]. Moreover, it is also worth mentioning that the World Health Organization (WHO)[4] estimates a good VA expressed in minimum angle of resolution (MAR) to be “1”. Notice that a good VA is in most cases well correlated with a sharp retinal image. Thus, by adding positive lenses this correlation changes, i.e., defocus produces blurred vision, which is translated into poor visual acuity.

Contrast sensitivity (CS) is the inverse of contrast threshold and is related to the ability of detecting differences in brightness between adjacent areas.[5,6] Its measurement determines the lowest contrast level that can be detected for a given or spatial frequency. The contrast can be calculated using the Michelson (1).

$$C_{Michelson} = \frac{(L_{max} - L_{min})}{(L_{max} + L_{min})} \quad (1)$$

When contrast sensitivity is obtained for a range of spatial frequencies it is possible to fit all contrast sensitivity thresholds into a function, namely, contrast sensitivity function (CSF).
The CSF provides more valuable information than visual acuity, which only considers high contrast. It is widely demonstrated that some diseases do not decrease visual acuity but have an impact on contrast sensitivity at lower spatial frequencies. An example of it is the well-known visual condition of cataracts.[7]
It is worth recalling the relationship between stimulus size and spatial frequencies. Low spatial frequencies can be well represented with broad black and white bands whereas a high spatial frequency grating has thin black and white bands. To this sense, when viewing distance and perspective are held constant, higher spatial frequencies correspond to smaller objects. Thus, the size of an optotype (e.g., Snellen character 'E') with a visual acuity of 1 (decimal scale) subtend to 5', and in terms of spatial frequencies it is equivalent to 30 c/d .[8]
In this case, adding positive lenses the image observed will be blurry because a loss of high frequencies is produced.[9] An schematic representation of the CSF and VA is shown in figure 1.

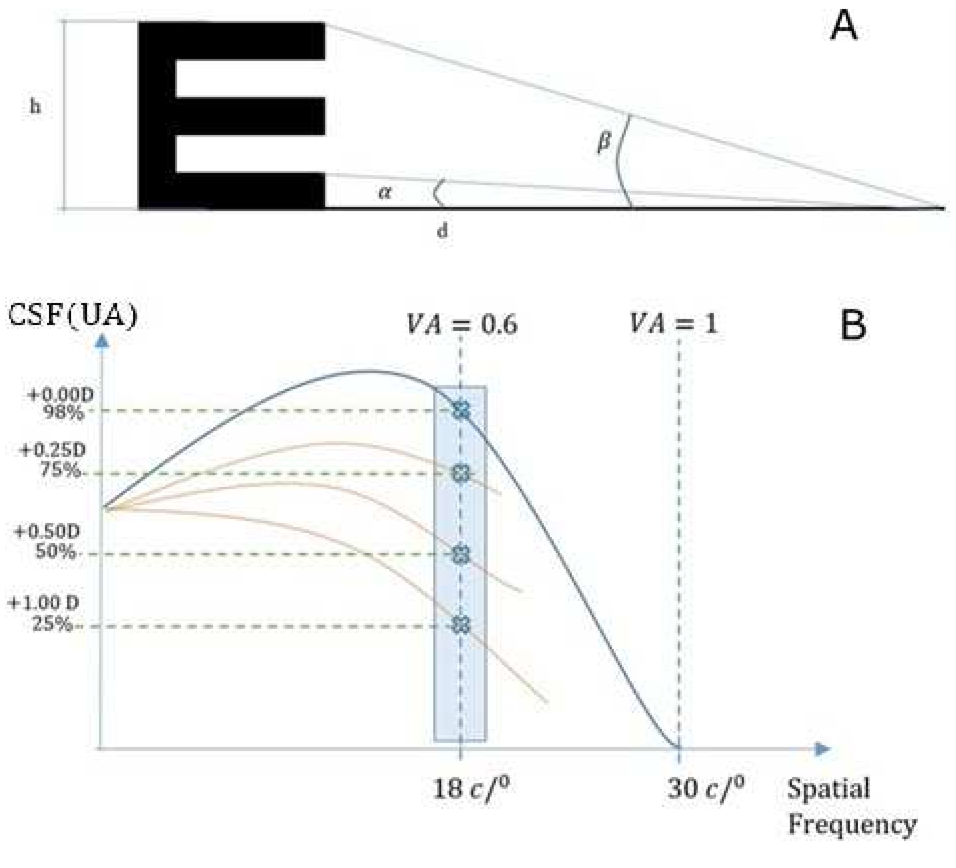

Figure 1. A) Snellen E optotype. h is the size of the optotype and d is the observation distance. The optotype subtends to β which comprises 5 times α (MAR). Notice that the inverse of 2 times α defines the spatial frequency of the optotype. B) The orange lines represent how it might change the CSF when defocus is added. When greater amounts of defocus are introduced into the visual system of a subject, less capacity will have the subject to perceive a stimulus with a very little contrast.

The purpose of this study is to explore the relationship between VA and CS at a certain spatial frequency (i.e., 18 c/d that is equivalent to $VA = 0.6$) through different levels of defocus (from 0.00 D to +1.25 D in 0.25 D-step). VA and CS should fall as more defocus is introduced. It may be possible to have a direct relationship between a certain VA (maximum contrast) and a certain contrast at lower spatial frequencies. This relationship can have an impact on technologies such as virtual reality. They have suffered a massive technological development in the last years getting a great number of applications in the industry. However, there is an important limitation in all of them, the optical resolution of the system. It is well known the existence of a trade-off between the field of view and the resolution of a virtual reality display. Typically, the larger the FOV, the worse the resolution given a fixed pixel size. Vision scientists are concerned with the impossibility to represent MAR's of 1' in current virtual reality technologies and at the same time having a reasonable field of view of at least 30º. Thus, it is difficult to test VA in such technologies. In order to overcome this limitation, it is of great interest to investigate the linkage between VA and other visual parameters such as CS.

2. Methods

Subjects

The study followed the tenets of the Declaration of Helsinki, and all subjects gave informed written consent. The subjects were recruited from the staff of Davalor Research Centre (UPC, Terrassa), staff of CD6 (Centre for Sensors, Instruments and Systems development, UPC, Terrassa) and friends. Criteria for inclusion were best corrected visual acuity of 0.10 logMAR or better and no history of any ocular condition, surgery and/or pharmacological treatment. Only one eye of each subject was included in the analysis and corrected with spherical and cylindrical components of over-refractions within ±0.25 D. There was not a minimum age requirement.

Experimental setup and examination protocol

First, an optometric examination was performed. The subjective refraction was measured with the endpoint criteria of maximum plus power consistent with best vision. The eye with best visual acuity was chosen for the measurements.

After that, participants were moved to the measurement room. A complete session in the experiment lasted around 45 minutes for patient. All the measures were done in the same lab and under constant room lighting conditions (photopic conditions). To minimize the effects of accommodation (the capability of the eye to focus near targets) all subjects were asked to sit at 6 meters distance from the screen (Philips LED 233V5LSB/00, Netherlands) in which the stimuli were displayed. The screen size was 58.4 cm, screen brightness was set to 250 cd/m^2 and gamma correction to 2.2.

To determine both the contrast sensitivity and visual thresholds for different defocus levels a psychophysical procedure called QUEST was performed monocularly (i.e., one eye was occluded with an eye patch). Defocus was optically induced adding spherical plus lenses in a trial frame, the defocus levels comprised from 0.00 Dioptres to +1.25 D (0.25 D-step). In total each subject had to do 12 times the psychophysical procedure, 6 of VA and other 6 for CS.

The psychophysical procedure QUEST was based on a two-alternative forced-choice task (2AFC) and the stimulus consisted in all cases on a Snellen 'E' that could point either to the left or right direction. Each QUEST test consisted in 64 trials were subjects had to indicate on a keyboard the direction of the 'E' letter. Each trial was shown 0.2s on the screen. The psychophysical experiment was performed in Matlab R2014 using a customized version of the QUEST function from the Psychtoolbox.

Psychophysical procedure

The fastest psychophysical method was developed by Watson and Pelli[8] 30 years ago. It is the Bayesian adaptive psychophysical method QUEST. There are two important concepts to mention about this psychophysical procedure.

On the one hand, the Bayesian methodology[10] is based on the Bayes rule which states that it is possible to calculate the posterior conditional probability of an event (Ak) given the event B (p(Ak|B)), if it is known the prior probabilities of a set of n events (p(Ai), i=1:n) and the conditional probability of an event B given a particular prior probability (p(B|Ai)). In other words, the Bayesian methodology needs to specify some prior knowledge on the parameters of a given model and to update knowledge of the unknown parameters conditioning the probability of this model to the observed data.[11] From a formal and mathematic view, [12] the Bayes' theorem, can be expressed in the following way

$$p(A_k\,|B) = \frac{p(B|A_k)}{\sum_i p(B|A_i)\,p(A_i)} \cdot p(A_k) \tag{3}$$

The QUEST method applies this theory to data collected in the experiment on each trial to update the posterior probability estimates of a specific parameter in order to converge into a value, i.e., the threshold we are looking for.

On the other hand, all psychophysical methods fit all the data obtained into a monotonic probability function. This function is called psychometric function and there are different mathematical models to represent that. Concretely, the QUEST procedure uses the Gumbel-Weibull distribution ($\Psi_T(x)$), which expresses probability as a function of log threshold intensity in decibels (i.e., the probability function has a logarithmic form). It has the following form

$$\Psi_T(x) = (1-\delta) - (1-\gamma-\delta)\exp\left[-10^{\left(\frac{\eta}{20}\right)(x-T-\tau)}\right] \tag{4}$$

The parameter γ specifies the chance level, since the experiment of this study is a two-alternative force choice task this value corresponds to 0.5. The value η specifies the slope of the psychometric function, typically, it is set to 3.5 for this kind of experiments. The parameter δ is the lapse rate (set it this study to 0.01), which sets the highest performance level at less than 100%, in other words, it is the probability of failing a trial despite the stimulus is well recognized. Finally, τ is associated with the proportion correct for the selected threshold performance level, it can be found empirically and in other similar studies it was set to -1.15 dB. The only parameter to estimate is the value *T*, the log threshold for a probability of correct responses of 75%. The estimation of T is updated each trial and the value of the next stimulus to present in each trial is the mode of the QUEST function (5). The QUEST function is the log posterior distribution of threshold *T* after trial *n*, based on the Bayesian update rule.

$$Q_n(T) = lnf_n(T) + \sum_{i=1}^{n}\{r_i ln\Psi_T(x_i) + (1-r_i)\ln[1-\Psi_T(x_i)]\} \tag{5}$$

If the subject fails, $r_i = 0$, otherwise $r_i = 1$. Therefore, if the subject fails $r_i ln\Psi_T(x_i) = 0$ meanwhile if the subjects success $(1-r_i)\ln[1-\Psi_T(x_i)] = 0$. In practice, when subject did the test of VA, if the patient's answer was right the letter changed to a smaller size, whereas if the patient's failed it changed to a larger size. Similarly, in the test CS, when the subject was right, the stimulus decreased its contrast making it more difficult to be seen. If the subject failed, the contrast was increased to a maximum of 95% contrast.

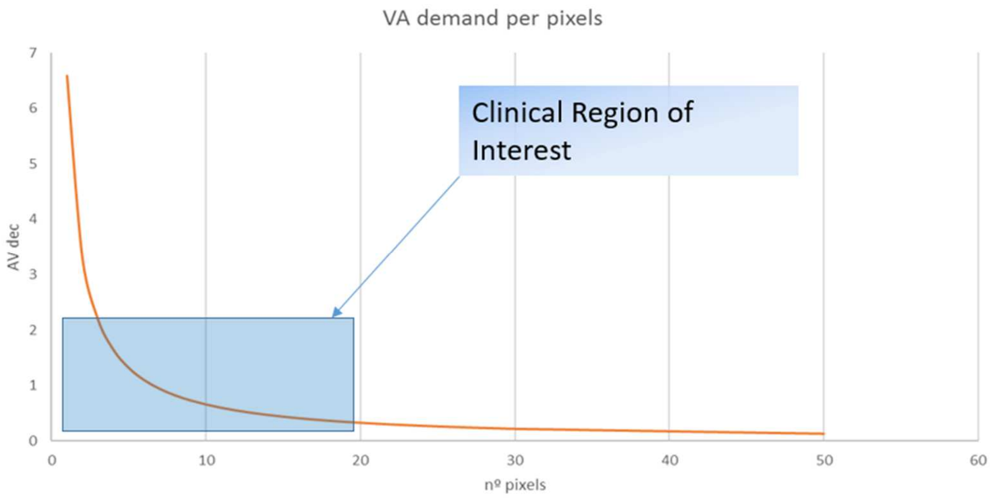

Figure 2. The relationship between nº of pixels and the VA decimal have got a perfect shape of potential. ($R^2 = 1$). For instance, if the stimulus uses only one pixel, the VA demand will be of 6.59 (certainly unobtainable), a stimulus of six pixels have got a VA demand of 1.10 or a stimulus of 30 pixels have got a demand of 0.22.

Relationship between the stimulus and the pixels.
Each pixel had a size of 0.265 mm^3, thus, considering that a letter should have a proportion equal to 5 times the stroke width and setting the viewing distance of the display to 6 m it is possible to exactly know the VA that can be shown in the screen. In figure 2 it can be seen the relationship between the number of pixels and the VA for our experimental conditions.

Statistical analysis
Data was preprocessed with Matlab R2014 (Mathworks Inc., USA). The significance was set at 0.05 and the statistical analysis was performed using SPSS v22 (IBM Corp., USA). Normality of each variable was checked with the Shapiro-Wilk test and correlations between CSF and VA for each pair of defocus are performed.

3. Results

Twenty subjects participated in this study with a mean age ± standard deviation of 20 ± 31.12 years (22 to 67 years) with mean corrected logMAR visual acuity of -1.49 ± 2.24 (+0.75 to -5.25). The data obtained followed a non-normal distribution according to the Shapiro-Wilk[13] test, thus, the best descriptors of central tendency and dispersion are the median and the interquartile range. In table 1 is shown the central tendency of the data and the values inside brackets reflect dispersion. In order to perform direct comparison between VA and CS, in figure 3 it is represented the box plots obtained from the normalized data shown in table 1.

Table 1. Descriptive statistics

	Defocus 0.0 D	Defocus 0.25 D	Defocus 0.50 D	Defocus 0.75 D	Defocus 1.00 D	Defocus 1.25 D
CSF	10.75 (13.90)	8.76 (11.02)	5.40 (8.18)	3.15 (4.83)	2.51 (4.54)	1.15 (1.91)
VA	1.65 (1.10)	1.32 (0.55)	1.10 (0.66)	0.82 (0.77)	0.60 (0.19)	0.51 (0.45)

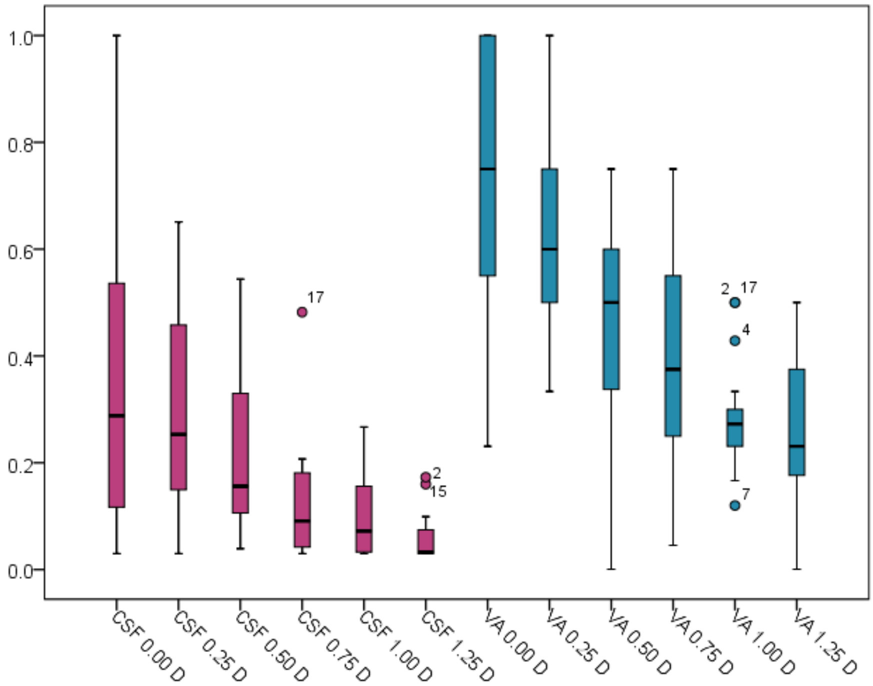

Figure 3. Box plot with normalized values for all parameters.

Table 2. Spearman correlation between de CSF and Visual Acuity values for each defocus level.

	Defocus 0.00 D	Defocus 0.25 D	Defocus 0.50 D	Defocus 0.75 D	Defocus 1.00 D	Defocus 1.25 D
Spearman's Rho	0.64	0.83	0.63	0.52	0.54	0.50
p-value	0.03	<0.01	0.04	0.10	0.09	0.12

To be illustrative with the fairly unknown adaptive bayesian psychophysical procedure QUEST, in figure 4 it is plotted an example of the performance of the QUEST psychophysical procedure when obtaining the CS threshold (figure 4A) and the VA threshold (figure 4B) along trials. In these two examples the method seems to converge well with 64 trials. Initially the letter size or letter contrast fluctuates greatly depending on the response of the subject. When the orientation of the stimulus is correctly guessed, size or contrast decreases abruptly. Then, if the subject fails, the size grows or contrast is accentuated, but to a lesser extent. Gradually the algorithm converges, to the smallest or least contrast value that the subject can see. The larger fluctuations have to take place in the first trials while the changes in the last trials should be very smooth showing all the answer are converging to the threshold of the patient.

Nevertheless, the QUEST procedure did not converge as good as expected in some patients. An example of it is shown in figure 5. As you can see in figure 5A, contrast seems to gradually decrease even after 64 trials. Moreover, in figure 5B it is not expected whatsoever an abrupt fall beyond the trial number 50.

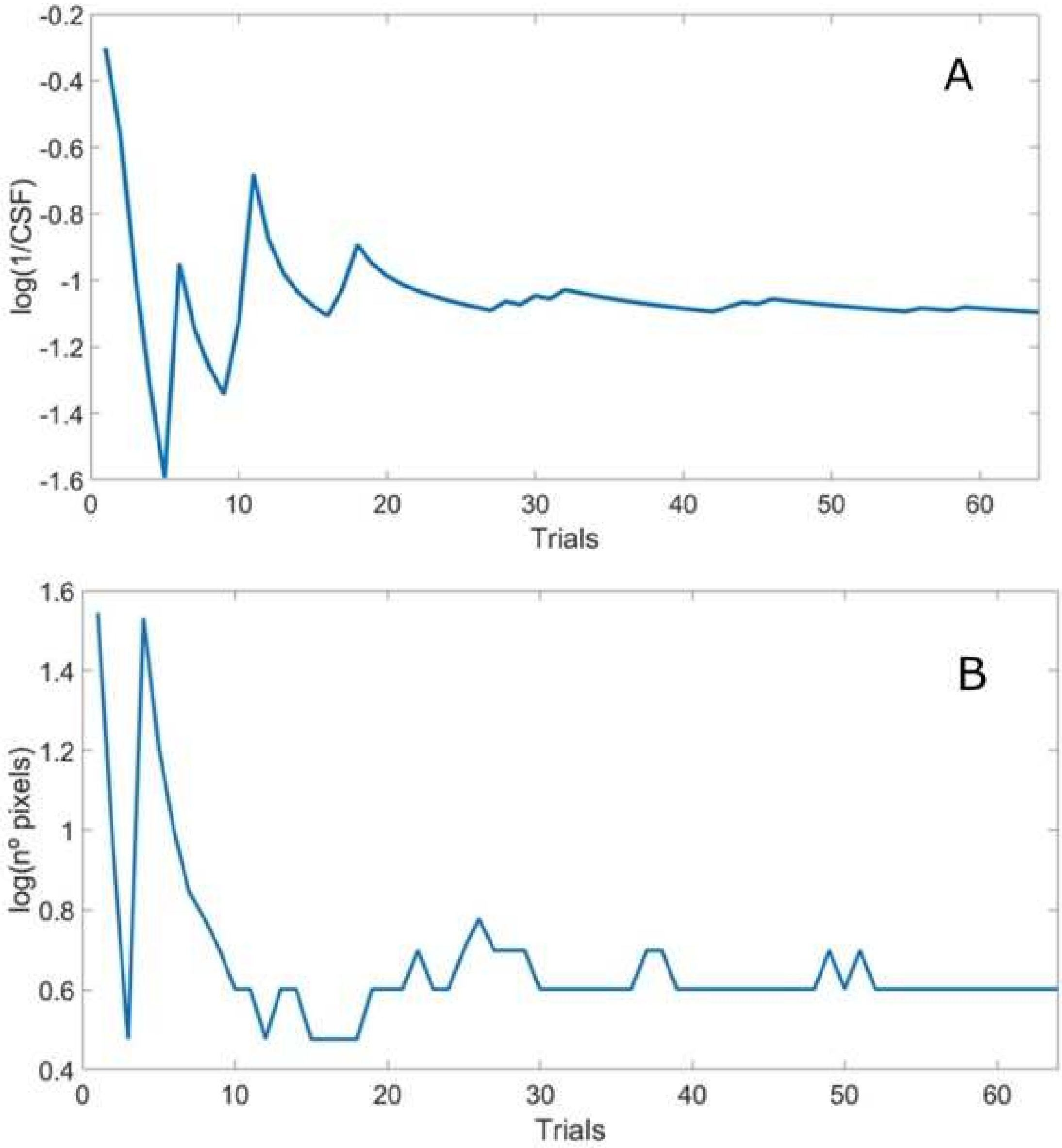

Figure 4. Example of good convergence during QUEST psychometric procedure. A) Log(contrast) values shown at each trial for patient #1 and defocus 0.00 D, B) Log(number of pixels) values shown at each trial for patient #1 and defocus 0.00 D. Notice that Visual Acuity is a function of the number of pixels.

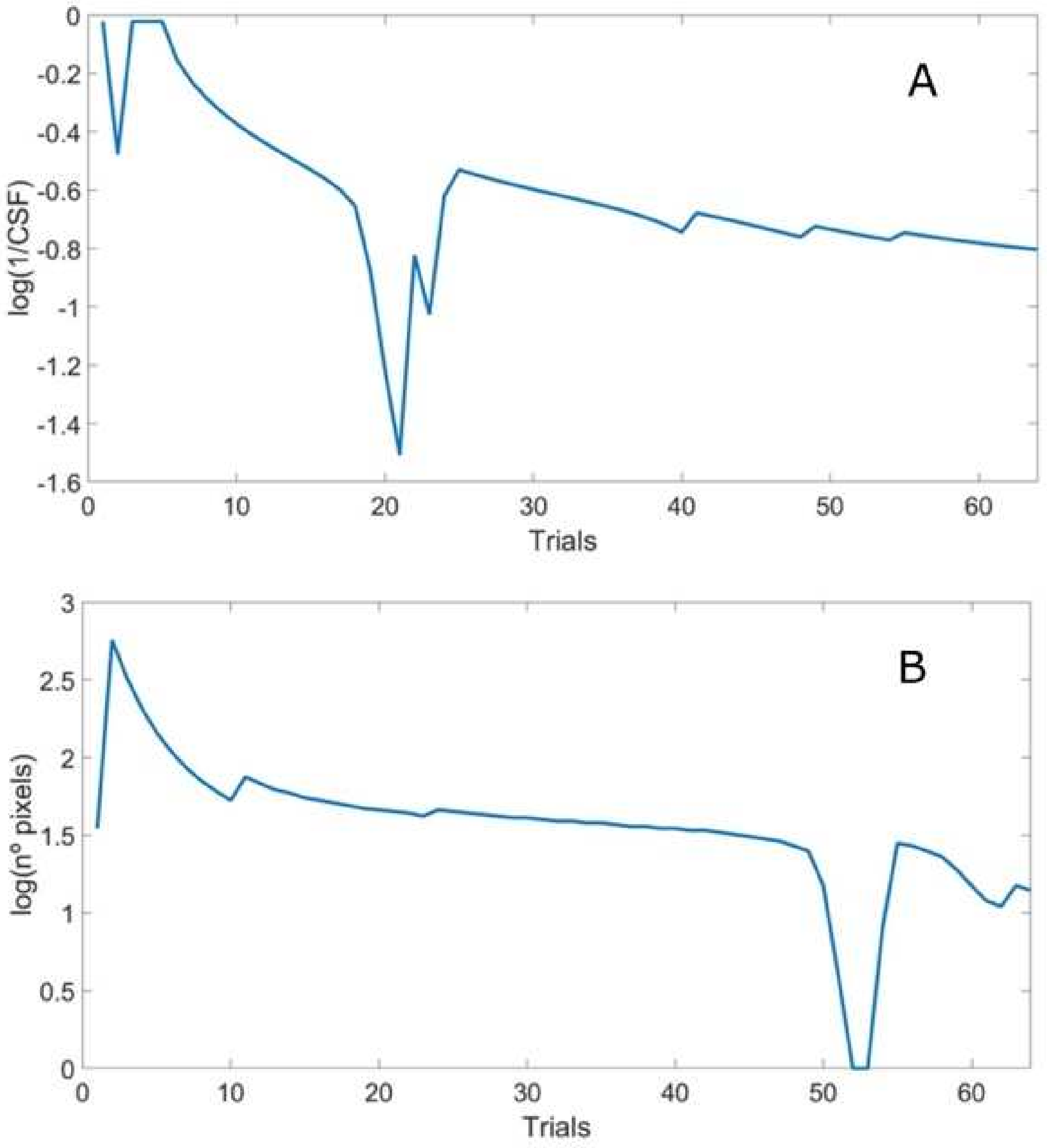

Figure 5. Example of bad convergence during QUEST psychometric procedure. A) Log(contrast) values shown at each trial for patient #15 and defocus 0.00 D, B) Log(number of pixels) values shown at each trial for patient #8 and defocus 0.00 D. Notice that Visual Acuity is a function of the number of pixels.

4. Discussion

In was explored in this study the correlation between CS (at 18 c/d) and VA at 6 different levels of spherical defocus.

First, as expected, VA and CS decreased with defocus, and more concretely, VA decreased faster than CS, which is also expected since higher spatial frequencies are more sensitive to defocus, and VA thresholds of our participants correspond to optotypes with greater spatial frequencies than 18c/d.

Secondly, all correlations between VA and CS thresholds are equal or greater than 0.5. Indeed, these correlations can be considered good enough considering a psychophysical experiment with human subjects.[14] However, there is a clear difference between the results obtained with defocus comprised between 0.00 D and 0.50 D and the results obtained with defocus comprised between

0.75 D and 1.25 D. For the lower levels of defocus, correlation is statistically significant ($p < 0.05$) but the results obtained with a defocus of 0.75D or higher shows a statistically insignificant correlation ($p>0.05$).
These results suggest that potentially, there might be a direct relationship between CS at a certain frequency and VA. This is an important finding since it can be used to overcome the maximum angular resolution of virtual displays without changing the pixel size nor the size of the field of view, namely, considering a high-contrast grating of specific spatial frequency, we might find a perceptually equivalent grating (in terms of a recognition task) with lower contrast and lower spatial frequency.
Despite these findings show promising correlations, it is crucial to disclose all sources of error in our data sets. An important aspect to mention from our results are the large dispersion shown in the interquartile ranges (table 1) and also in the boxplots from figure 6. It is likely due to a fairly small sample size (n=20). Even though the sample chosen for this study is enough for an exploratory analysis (as it is done in this study) it has the inconvenient of larger variabilities. However there are other factors that might account for this dispersion as well, among them we must note that participants were not homogeneous in terms of age (i.e., subjects were from 22 to 67 years old) and it is well-known the influence of age on visual acuity and contrast sensitivity.[15]
Thus, age is probably a cofounding factor in our data sets. If sample size had been larger it would have been convenient to add age as a covariate.
Additionally, contrary to what we expected, we detected some cases in which the QUEST procedure did not converge well in both the CS and VA threshold determination (two examples are shown in figure 5A and 5B). This is somehow surprising since it is reported elsewhere that with 64 trials each QUEST procedure is enough for convergence[3].
In order to overcome all these limitations in further studies, it is required to increase notably the numbers of subjects, split data analysis in different subgroups of age and increase the number of trials. All these would likely diminish the dispersion.
Finally, it is also worth mentioning that the perceived level of illumination is subjective and different in each case and can depend on other factors such as the state of pre-adaptation of the eye, the observation’s time, the area of the retina that is stimulated, luminance contour and color stimulus.
Indeed, the exposure time may have been a key problem. The exposure time of the stimulus was so short (0.2 seconds) that the subject practically looked all the time at a white screen on a white background (the wall behind the monitor was white). This exposure time is already used in other similar psychophysical experiments. However, it is fair to think that participants may have suffered -to some extent- from the so-called phenomena of photobleaching. Both cones and rods (photoreceptors present in the retina) contain some photopigment molecules, which play a fundamental role in phototransduction (transforming light into an electrical signal). The photo pigments of the cones are different to those present in rods. When light reaches the eye in a continuous fashion it can occur that the concentration of the photopigments is affected in such a way that the ability of the photoreceptors to absorb light is decreased, until reaching a saturation. As the intensity of the luminance of the adaptation field increases, it decreases the number of photo pigments capable of absorbing light. Due to this, several subjects could not properly see the stimulus appearing in the screen.
The exposure time of the stimulus could lead also to a secondary problem. As the stimulus was presented very fast, the subjects tended also to respond very quickly, inducing some false negatives (more than 1 trial per each QUEST test). This issue is theoretically taken into account in the lapse rate parameter of the QUEST procedure. This parameter is the probability of failing a trial despite the stimulus is well recognized. In this study we set a lapse rate of 0.01 (i.e., 1%), which corresponds to less than 1 trial for each QUEST test, but considering the above mentioned, it might have been appropriate to increase this value to be more representative of our experiment.

Other minor changes that we believe it can improve the results can be a sound providing auditory feedback after each participant's answer, a screen of different color between each stimulus presentation in order to reduce photobleaching, and obviously to increase the number of subjects and trials per subjects.

5. Conclusion

Finding the way to link psychophysically, in a recognition task, the VA and the CS at a certain spatial frequency will allow to overcome the limit in VA currently present in most virtual reality displays in terms of visual perception. In this study we explored this linkage and we showed that it is potentially plausible to find a perceptual balance between both psychophysical measures. Correlation between VA and CS at 18 c/d is good in 6 different levels of spherical defocus ranging from 0.00 D to +1.25 D.

Despite our results showed large variabilities in all data sets, this exploratory study has characterized and disclosed all the most important sources of error and has established a good starting point for a larger scale further study with a much larger sample size.

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References

1. Atchison D, Smith G. *Optics of the Human Eye*. 1st ed. Butterworth-Heinemann; 2000.
2. Martín R, Vecilla G. Agudeza visual. In: *Manual de Optometría*. ; 2011:2-21.
3. Lu, Zhong Lin BD. *Visual Psychophysics: From Laboratory to Theory*. Vol 43.; 2014.
4. Adeoti CO, Ubah JN, Isawumi M a, Ashaye a O, Oluwatimilehin IO, Raji R a. *Visual Standards: Aspects and Ranges of Vision Loss*. Vol 14.; 2007.
5. Faye EE. Contrast sensitivity tests in predicting visual function. *Int Congr Ser*. 2005;1282:521-524.
6. Owsley C. Contrast sensitivity. *Ophthalmol Clin North Am*. 2003;16(2):171-177. doi:10.1016/S0896-1549(03)00003-8.
7. López A Y. Importancia de la valoración de sensibilidad al contraste en la práctica optométrica. *Cienc Tecnol para la Salud Vis y Ocul*. 2009;7:99-114.
8. Pelli DG, Bex P. Measuring contrast sensitivity. *Vision Res*. 2013;90:10-14. doi:10.1016/j.visres.2013.04.015.
9. Brown Brian L-KJE. High and Low Contrast Acuity and Clinical Contrast. *Optom Vis Sci*. 1989;66, Nº7:467-473.
10. Bernardo JM. Bayesian statistics. *Encycl Life Support Syst*. 2003:1-46.
11. Marín JM. Tema 1 : Introduccion a la Estadıstica Bayesiana. *Univ Carlos III Madrid*. 2010:1-10.
12. Watson AB. Watson 1983.pdf. *Berlin SpringerVerlag*. 1983:100-114.
13. Wilk SSSMB. *An Analysis of Variance Test for Normality*. Biometrika

14. Heckenlively JR, Arden GB. *Principles and Practice of Clinical Electrophysiology of Vision, Page 957*. (Arden (Editors), ed.).; 2006.

15. Medina-Alvarez Tostado, L ; Díaz-Perez, JM; Durán-Iñiguez F. Sensibilidad al contraste visual en la poblacion mexicana sana. *Salud Publica Mex*. 1995;37(4):310 - .