OPO OPHTHALMIC AND PHYSIOLOGICAL OPTICS
THE JOURNAL OF THE COLLEGE OF OPTOMETRISTS

Ophthal. Physiol. Opt. 2010 **30:** 188–199

Quantitative and functional influence of surround luminance on the letter contrast sensitivity function

Juan A. Aparicio[1], Isabel Arranz[1], Beatriz M. Matesanz[1], Juan G. Vizmanos[1], Lidia Padierna[1], Víctor R. González[1], Santiago Mar[1], José A. Menéndez[2] and Luis Issolio[3]

[1]Departamento de Óptica, Universidad de Valladolid, P. Prado de la Magdalena s/n 47071 Valladolid, [2]Departamento de Estadística e Investigación Operativa Universidad de Valladolid, P. Prado de la Magdalena s/n, 47071 Valladolid, Spain, and [3]Instituto de Luminotecnia, Luz y Visión – CONICET, Universidad Nacional de Tucumán, Avenida de Independencia 1800, 4000 Tucumán, Argentina

Abstract

Aim: To determine the influence of surround luminance on the letter contrast sensitivity function.
Method: The binocular contrast sensitivities of 31 young and ocularly healthy individuals were measured with letters of sizes calculated to obtain the targeted fundamental frequencies of 3, 10, 20, and 30 c deg^{-1}, respectively; with surround luminances from 1 to 1000 cd m^{-2}, always with a test chart background luminance of 200 cd m^{-2}.
Results: The letter contrast sensitivity increased with surround luminance up to 100 cd m^{-2} and decreased when surround luminance increased from 100 to 1000 cd m^{-2}. These increments are larger for higher fundamental spatial frequencies, while decrements are similar for all frequencies. To analyse pupil size influence, results were compared with theoretical predictions obtained by combining different ocular MTFs with a typical neural function, where pupil size decrease leads to letter contrast sensitivity increments and veiling luminance causes the observed decrements. Other possible optical or neural factors that influence these values have also been considered.
Conclusions: Letter contrast sensitivity function depends on surround luminance and this influence should be considered in future standardized directives.

Keywords: contrast sensitivity, glare, psychophysics, vision

Introduction

The contrast threshold is the lowest amount of contrast required to detect, discriminate or identify a target. Contrast sensitivity (CS) is the reciprocal of the contrast threshold (Higgins *et al.*, 1996; Strasburger and Rentschler, 1996). Contrast sensitivity complements visual acuity in the evaluation and assessment of visual capabilities. It has also been recognized as a potentially useful tool in early detection of visual system diseases (Regan and Neima, 1983). However, the lack of comprehensive standards, especially those concerning the environmental lighting conditions under which the tests should be performed, means that the CS or letter CS measurements are of limited clinical value, due to the difficulty in comparing and interpreting results (Long and Penn, 1987; Scialfa *et al.*, 1988; Rabin, 1994; Bach *et al.*, 2008). This is particularly critical if the results are to be used for screening or for monitoring the development of pathology.

Many studies have examined the influence of test and surround luminance on visual acuity measurements (Lythgoe, 1932; Shlaer, 1937; Patel, 1966; Sheedy *et al.*, 1984). This has allowed the development of standardized

Received: 14 January 2009
Revised form: 29 June 2009; 2 September 2009; 13 October 2009
Accepted: 22 October 2009

Correspondence and reprint requests to: Juan A. Aparicio.
Tel.: +34 983 423267; Fax: +34 983 423013.
E-mail address: apa@opt.uva.es

doi: 10.1111/j.1475-1313.2009.00707.x

directives or recommendations concerning visual acuity optotypes and their presentation (National Academy of Science, National Research Council (NAS-NRC). Committee on Vision, 1983; International Organization for Standardization (ISO) (1996); American National Standards Institute (ANSI, 2004). The situation is not so clear with CS measurements. It is certainly well known that contrast sensitivity measured with optotypes or sinewave gratings decreases with decreasing stimulus luminance (Blackwell, 1946; de Valois *et al.*, 1974; Kelly, 1977; Banks *et al.*, 1987; Sucs and Uvijls, 1992; Puell *et al.*, 2004), but there is limited information about the quantitative and functional influence of surround luminance on the letter contrast sensitivity function.

With respect to the influence of luminance, three studies should be considered. Coletta and Sharma (1995) measured CS with laser interference fringes imaged directly onto the retina as a function of the luminance of incoherent light added to the retinal field. These results are difficult to apply in the clinical environment since the influence of the optical properties of the eye is minimized when using this kind of experimental arrangement. Cox *et al.* (1999) measured letter contrast sensitivity with Pelli–Robson letter charts and the contrast sensitivity function (CSF) with sinewave gratings displayed on a monitor under different surround luminance conditions. The authors observed a strange discrepancy in that there was a different influence of surround luminance on the contrast sensitivity dependent on whether this was measured with letter charts or sinewave grating tests. Both types of tests were applied to a small number of participants in a surround luminance condition which showed a certain lack of spatial homogeneity according to the photographs included in the paper. Furthermore, letter chart tests of only two fundamental spatial frequencies, both lower than 4 c deg^{-1}, were employed so that not much information was provided concerning the influence of surround luminance on the of the CSF overall. Khanani *et al.* (2004) measured contrast thresholds for Sloan letters under different conditions of luminance. Compared with the previous work, these authors incorporated up to 30 participants who had to detect Sloan letters of three fundamental spatial frequencies (8, 12 and 20 c deg^{-1}). However, they considered only two illuminating conditions so that the functional influence of surround luminance was not provided.

In clinical practice there are concerns about which test should be employed to measure CS. Letter contrast sensitivity involves a task of low-contrast letter recognition, whereas contrast sensitivity usually involves the detection of a stimulus (grating or Gabor patch); or discrimination of a low number of stimulus alternatives. There are not only differences in frequency content between the two types of tests, but also in the neural mechanisms involved (Strasburger *et al.*, 1991, 1994; Strasburger and Rentschler, 1996). In favour of letter identification, it is recognized that this task is more familiar for observers and does not require special teaching or training. However, commercial charts for letter contrast sensitivity measurements have important drawbacks. The Pelli–Robson letter chart allows measurement of CS for only one fundamental spatial frequency unless it is employed at different distances from observer. Sixteen contrasts which differ by 0.15 log units are evaluated. Low-contrast letter acuity test charts can measure contrast sensitivity for medium-high and high spatial frequencies but only five contrasts are available. We can conclude that typical CS letter charts either cannot provide global information on the spatial frequency domain or may miss small changes in contrast sensitivity. Existing computer-based methods for measuring contrast sensitivity are reliable, precise, and simple-to-use, although they need regular calibration (Bach, 1996; Strasburger, 1997; Colombo *et al.*, 2009). These tests have not been considered in this study because we were interested in clinical practice where tests based on printed charts are more common. In the case of letter contrast sensitivity in particular, printed charts provide a simple and effective means to investigate the influence of surround luminance on CS.

For this study, a specific letter contrast sensitivity test based on printed test charts was designed in order to overcome most of the drawbacks identified. All letters appearing in each chart had the same size, each contrast was represented by three grouped letters and the difference between consecutive contrasts was 0.04 log units in average (increments in 10% between consecutive groups). This yields a significant improvement in the ability to detect small changes in the letter CS. Four estimated fundamental spatial frequencies were considered (3, 10, 20 and 30 c deg^{-1}). Measurements have been performed for a very broad range of surround luminances (1, 10, 100 and 1000 cd m^{-2}) and for a background luminance of the test chart of 200 cd m^{-2}, with special attention paid to the homogeneity of the illumination.

Methods

Subjects

The principles of the Declaration of Helsinki were followed. Thirty-one individuals served as observers, 20 female and 11 male, with ages ranging from 19 to 24 years (mean 22.0 and standard deviation 1.6 years). They were all students at the Science Faculty of the University of Valladolid and gave informed consent prior to any observation or measurement. After answering a questionnaire, all candidates were examined with ophthalmoscope and biomicroscope. Subjects with a history of amblyopia, eye disease, squint, marked anisometropia, defect or lack of transparency in their ocular media, or any other abnormal observation during the optometric examination were excluded. Those who took drugs or any kind of medication prior to refraction or measurements were also excluded.

All selected candidates were refracted for long distance vision in a room with good lighting conditions. The aim during all refractions was to obtain the maximum visual acuity (Jansonius and Kooijman, 1997; Atchison *et al*., 1998; Strang *et al*., 1999; Woods *et al*., 2000; Radhakrishnan *et al*., 2004). Candidates who were users of contact lenses were asked not to use them for at least 2 days prior to the experiment. Finally, all candidates with binocular visual acuity lower than Snellen 20/20 (logMAR 0.0) with their best optical corrections were also excluded. The best correction was provided in spectacle form in all cases, including habitual users of contact lenses. Overall, the binocular visual acuity of our subjects ranged from Snellen 20/16 to 20/10 (logMAR −0.08 to −0.32) although 90% of these values ranged from Snellen 20/12 to 20/10 (logMAR −0.18 to −0.32). If we consider that only 15% of the initial volunteers were rejected, we can conclude that the selected participants in this study, and the results obtained, are representative of a young population.

Experimental arrangement

A scheme of the experimental set-up is shown in *Figure 1*. The experiment was carried out in a 6 × 3 × 3 m (length × width × height) room with white painted walls, isolated from outside light. A white matte cork wall was built and a specifically designed square box (0.7 × 0.7 × 0.7 m) was placed behind it. This was matte white painted inside. The inner part of the box is visible through a 0.3 m diameter circular hole in the cork wall. This hole acted as a window for the observer. A constant and homogeneous intensity of light inside the test box was provided by four stabilized incandescent lamps.

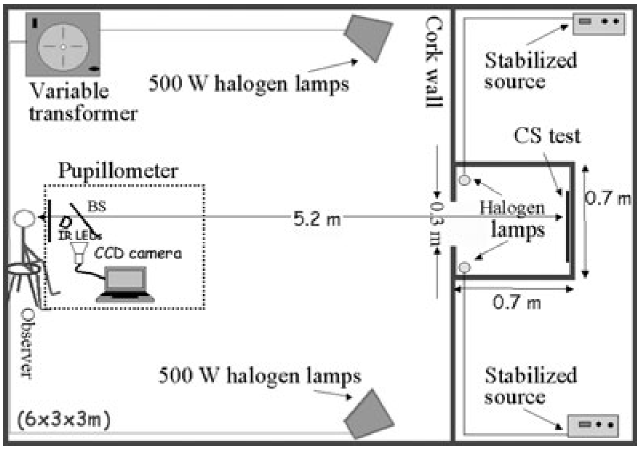

Figure 1. Experimental arrangement.

The cork wall was illuminated with eight 500 W lamps, connected to a variable transformer. This arrangement allowed the cork wall to behave as a surround which provided an adjustable luminance from darkness to 1000 cd m^{-2}. Luminances outside the cork wall were lower than 10% of surround luminance. After reviewing different recommendations found in the literature (International Organization for Standardization (ISO), 1996; American National Standards Institute, (ANSI), 2004), a value of 200 cd m^{-2} was selected for the background luminance of the test chart because this is the mean value recommended in these directives. All luminances were measured with a Spectra Pritchard model 1980A luminance meter. Variations in luminance across the test were lower than 2% and the inhomogeneities in the surround luminance spatial distribution were lower than 15%. Reflections or glare sources from tests/targets or surround were avoided.

A pupillometer was designed to measure the pupil size. Light coming from eight infrared LEDs (peak of intensity at 820 nm) illuminated the observer's pupil and an image of it was registered by a CCD camera equipped with an infrared (IR) filter which blocked the visible light. The camera was connected to a computer where the pupil images were saved and analysed in order to measure pupil diameters. Pupil size measurements were calibrated with the help of a ruler placed as close as possible to the entrance pupil plane. Uncertainty of this parameter has been estimated from the standard deviation of the measured pupil sizes for each individual. The greatest ratio between standard deviation and mean pupil diameter is $<2\%$.

A test chart with letters was designed as justified above: it allows measurements of four significantly different spatial frequencies with a greater resolution for detecting subtle changes than most commercial contrast sensitivity tests. In order to avoid memorizing effects during measurements, four versions of each test were designed. In each version, letters corresponding to the same contrast and size were different. Each chart contained square letters of a size s (61.0, 18.2, 9.1 and 6.1 mm) calculated to obtain the targeted fundamental frequencies of 3, 10, 20, and 30 c deg^{-1}, respectively, when viewed at a distance of 5.2 m. The sizes were calculated by assuming the criterion of 2.0 cycles per letter for optimal letter recognition (Legge *et al*., 1985). This value is intermediate between the 2.5 cycles per letter proposed by Pelli *et al*. (1988) and the 1.5 proposed later by Akutsu *et al*. (2000). Each test consisted of a single sheet of paper containing eight rows of two triplets each, except the test corresponding to the largest letters (3 c deg^{-1}), which consisted of three sheets of paper, each one containing two lines with one triplet each. Inter-letter separation was at least one letter with the exception of the 3 c deg^{-1} charts in which this was slightly lower. All letters were selected from the 10 Sloan letters: D,H,N,V,R,Z,S,K,O and C (Sloan, 1951). A specific Sloan computer font was created by the authors. An example of the test chart used for measuring letter CS at 30 c deg^{-1} is shown in *Figure 2*.

The letters test charts were produced using the five different print qualities of a Hewlett–Packard HP9800 deskjet printer: quick draft, draft, normal, optimum and maximum dpi. The different grey shades were printed as patches 59 × 19 mm on a DIN A4 quality office paper for contrast measurement. They were photometrically calibrated using the luminance meter 6′ test spot at 2 m from the paper. This spot is large enough to obtain stable measurements and small enough to avoid the reduction of contrast due to light coming from the surround of the shaded patch. The Weber contrasts obtained ranged from 90% to 0.25% (log C ranged from −0.045 to −2.60) with steps which depended on the contrast. Contrasts of consecutive triplets decreased in a logarithmic scale by steps of 0.04 log units on average.

Figure 2. An example of the CS test for letters of 6.1 mm size (estimated fundamental spatial frequency of 30 c deg^{-1}) designed and employed in this experiment.

Procedure

Observers were 4.5 m away from the cork wall, that is to say, 5.2 m from the test chart. From this distance, chart and surround subtended 3.8 and 33.8 degrees, respectively, both vertically and horizontally. All measurements were binocular to obtain maximum visual performance (Rabin, 1995). Previous trials performed on individuals with high and low visual acuities allowed us to determine, for each estimated fundamental spatial frequency, the range of contrasts which should be employed in the corresponding test. For each observer, 16 CS measurements were made, which correspond to all combinations of the four letter sizes and the four surround luminances L_s. This set of measurements was performed once for each observer, and the order of measurements was randomised for each subject.

Subjects were asked to read from the top of the chart and encouraged to guess the letters even when they were not clear (Pelli *et al.*, 1988). Letter CS was recorded as the inverse of the contrast of the last group of letters in which two out of three letters were identified correctly. There was no time limit. Prior to each trial a 10 min period was given to allow the observers to adapt to the illumination conditions. This is considered as a sufficient time to elicit maximum pupil dilation for each specific lighting condition (Brown *et al.*, 2004). The whole set of measurements for each observer lasted for 3 h approximately. For these long sessions of measurements, a chin rest was considered too uncomfortable. Instead, the observers were encouraged to concentrate on the tests and to move as little as possible. No attempt was made to alter natural pupil size.

For 10 observers, pupil size measurements were performed under the four illumination conditions considered here. The 18.2 mm (10 c deg^{-1}) letter size was used as a fixation target. With the experimental conditions previously described, possible miosis effects due to accommodation (Iwasaki and Tawara, 2002) can be considered negligible. Adaptation times were also of 10 min for each condition. The order of measurements was again randomly chosen. For each illumination condition, five pupil images of each eye were recorded and the average diameter d calculated.

Results

Mean values of letter contrast sensitivity for each letter size s and each surround luminance L_s are shown in *Figure 3*. As can be seen in this figure, the detected differences in letter CS for the different surround luminances are very small. It is also observed that, for L_t = 200 cd m^{-2}, letter contrast sensitivity increases as surround luminance L_s increases from 1 to 100 cd m^{-2}, showing a decrease as L_s goes from 100 to 1000 cd m^{-2}.

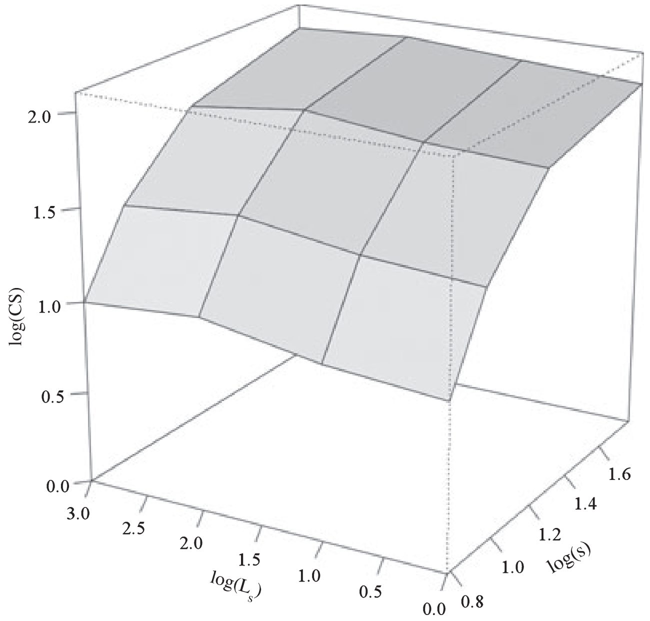

Figure 3. Influence of log surround luminance L_s (in cd m^{-2}) and log letter size *s* (in mm) on log letter contrast sensitivity (CS).

This behaviour seems to be reproduced for the whole range of letter sizes in this study, although from *Figure 3* alone, it is difficult to decide whether the influence is quantitatively similar for different *s*-values.

From a statistical point of view, the 16 measurements performed on each observer can not be considered as independent events. Each observer has a different visual acuity and observers with a higher visual acuity are known to exhibit letter contrast sensitivity which is higher than that of observers with a lower visual acuity. Furthermore, letter CS has a well known dependency on letter size. In this sense, a part of the variability observed in measured data is due to the inherent visual features of each individual while another part comes from the random factors involved in any experiment. In order to consider these effects and simultaneously to analyse both the influence of surround luminance L_s and letter size *s* on the measured contrast sensitivity, a mixed-effects linear model was fitted to the experimental log(CS) data. In this model *s*, L_s and the interaction $s \leftrightarrow L_s$ are considered as fixed effects while the effect *ind* (*ind* means individual) and the interaction $s \leftrightarrow ind$ are considered random effects. Both random effects are statistically significant. This has been verified by means of the deviance analysis. The components of the variance linked to both random effects ($\sigma_{ind} = 0.106$ and $\sigma_{s \leftrightarrow ind} = 0.069$) explain most of the observed variability on log(CS) data due to the fact that the differences between individuals take very similar values for all *s* and L_s-values. The residual variability is $\sigma_{res} = 0.076$. The interaction fixed effect $s \leftrightarrow L_s$ is also statistically significant ($p = 0.026$). In order to assess the reliability of the model used, a bootstrap procedure has also been performed and a similar *p*-value has been obtained. We can conclude therefore that, from a statistical point of view, the influence of surround luminance is different for different letter sizes (or estimated fundamental spatial frequencies according to the approximate conversion proposed above).

By considering a relatively low luminance condition of 1 cd m^{-2} as a reference, the differences between the obtained average log(CS) values and the average log value at $L_s = 1$ cd m^{-2} have been calculated for each letter size and surround luminance. These differences Δlog(CS) have been plotted as functions of log(L_s) in *Figure 4* for the four letter sizes considered. These plots therefore represent the global effect of an increasing

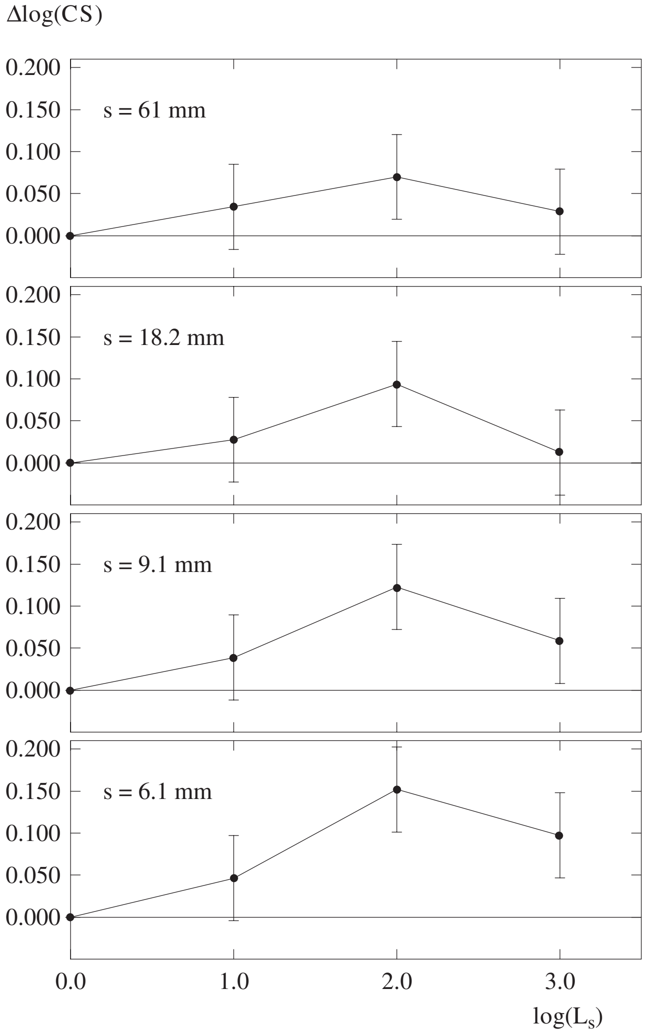

Figure 4. Changes in the log(CS) values induced by an increasing surround luminance by taking as reference the dark surround condition at four letter sizes (31 subjects). From top to bottom, these letter sizes correspond to the four fundamental spatial frequencies of 3, 10, 20 and 30 c deg^{-1} according to the approximate conversion proposed in the experimental arrangement section.

surround luminance on the letter contrast sensitivity which was measured in the dark surround condition. Under the conditions of the statistical model used, these $\Delta\log(\text{CS})$ values show a standard error around 0.0192. The calculated 95% Bonferroni corrected confidence intervals ($n = 12$) for $\Delta\log(\text{CS})$ are therefore ± 0.0506. These confidence intervals have been indicated in *Figure 4* by the corresponding vertical bars. Standard error calculations as well as confidence intervals for the $\Delta\log(\text{CS})$ values by bootstrap procedures yield very similar results.

As it is shown in *Figure 4*, all $\Delta\log(\text{CS})$ values are positive and for $s = 9.1$ mm (20 c deg^{-1}) and $s = 6.1$ mm (30 c deg^{-1}) these values for $L_s = 100$ cd m^{-2} and $L_s = 1000$ cd m^{-2} are statistically significant. For $s = 61$ mm (3 c deg^{-1}) and $s = 18.2$ mm (10 c deg^{-1}) a similar trend is observed. However only the value for $L_s = 100$ cd m^{-2} is significantly positive in these two cases. It is also observed in *Figure 4* that the highest $\Delta\log(\text{CS})$ value is reached, for all s-values, at the surround luminance of $L_s = 100$ cd m^{-2}. All these observations have been confirmed by bootstrap procedures. These procedures have also been employed to analyse the decrease observed in log(CS)-values when surround luminance increases from 100 to 1000 cd m^{-2}. This analysis has confirmed that the differences between these two values of log(CS) are statistically significant for 10, 20 and 30 c deg^{-1} ($s = 18.2$, 9.1 and 6.1 mm, respectively).

The most significant optical parameter which changes when varying the surround luminance is the pupil size. Measured average pupil diameters d are shown in *Table 1* as well as the resulting foveal retinal illuminances E for the different surround luminances L_s. E-values in photopic trolands (Td) were simply calculated from the expression $E = \pi d^2 L_t/4$, L_t being the test luminance. Foveal retinal illuminance decreases with squared pupil diameter, which decreases significantly as the surround luminance increases in this experiment. *Table 1* also contains estimated foveal veiling luminances L_v for the L_s-values used. The factor $(1 + L_v/L_t)$ shown in the table represents the value by which the foveal luminance (both that of the pattern and of the background) is increased, or the letter contrast decreased, due to the veiling luminance. When the luminance distribution in the observer's visual field is composed of concentric luminous rings centered on the fixation line, as very approximately happens in this experiment, veiling luminances for young people (20–30 years) in cd m^{-2} can be estimated according to the following expression (Adrian and Topalova, 1991):

$$L_v = 0.017608 \sum_{i=1}^{n} L_i(\ln\theta_{i+1} - \ln\theta_i), \qquad (1)$$

where L_i is the average luminance in each ring, expressed in cd m^{-2}, and θ_i in radians, are the angular limits of each ring as subtended from the observer. In this model the central 2 degrees of visual field are assumed not to contribute to the veiling luminance. As is shown in *Figure 5*, the veiling luminance is produced by two rings ($n = 2$) in our experiment. The first one corresponds to the peripheral part of the field subtended by the test. As seen from the observer, it has an angular size of 0.9 deg with $\theta_1 = 1$ deg and $\theta_2 = 1.9$ deg, where $L_1 = L_t$. The surround can be approximately considered as a second ring which subtends an angle of 15 deg as seen from the observer with $\theta_2 = 1.9$ deg and $\theta_3 = 16.9$ deg, where $L_2 = L_s$. As a conclusion, for $L_s < L_t$, the veiling luminance is dominated by the light from the test field; for $L_s > L_t$ it is dominated by the surround. It is also important to remark that, even though some authors (Abrahamsson and Sjöstrand, 1986) proposed to use a

Table 1. Pupil diameter (d) and foveal retinal illuminance (E) for the different surround luminances (L_s) of the experiment, and foveal veiling luminances (L_v) as calculated from Adrian and Topalova (1991). In all cases the background luminance of the chart test (L_t) was 200 cd m^{-2}

L_s (cd m^{-2})	d (mm)	E (Td)	L_v (cd m^{-2})	$1 + L_v/L_t$	$\log(1 + L_v/L_t)$
1	4.7	3470	2.29	1.011	0.005
10	4.0	2513	2.64	1.013	0.006
100	3.0	1414	6.10	1.030	0.013
1000	2.5	982	40.72	1.204	0.081

The fifth column contains the factor $(1 + L_v/L_t)$ by which retinal Weber contrast is reduced due to veiling luminance. Sixth column contains the log value of the factor.

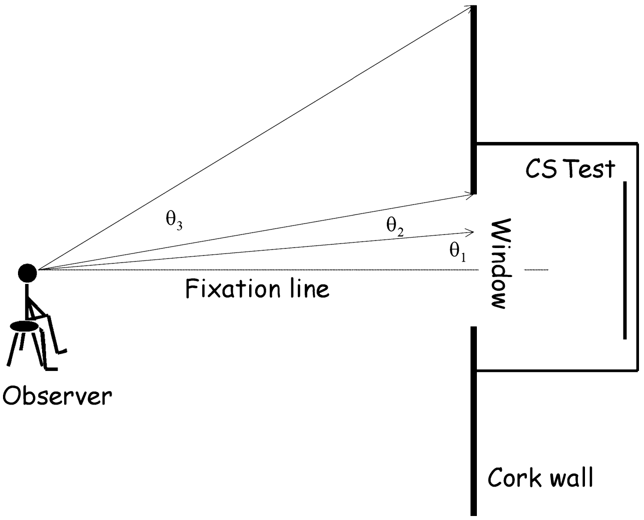

Figure 5. Angular limits of the concentric rings which produce veiling luminance on the retina due to glare effect. In our experiment $\theta_1 = 1$ deg, $\theta_2 = 1.9$ deg and $\theta_3 = 16.9$ deg.

pupil correction factor to quantify the effect of pupil diameter changes on CS in the presence of glare, other authors (Whitaker *et al.*, 1994) later demonstrated that the pupil changes affect the stimulus luminance and the veiling luminance in the same way, such that the ratio between them remains constant. In other words, although the corresponding retinal illuminance due to veiling luminance is pupil size dependent, the ratios L_v/L_t, which are the relevant data for the effect of glare, and their corresponding retinal illuminance ratios, should be independent of pupil size.

Analysis of pupil size effects

Among the optical factors which influence these results, pupil size may play a significant role. Pupil size changes gives rise to a change in the modulation transfer function (MTF) of the eye. Aberration or residual ametropias effects are also reinforced or diminished as pupil size increases or decreases, respectively. All factors together influence retinal image quality and this is also a key factor in the letter recognition process.

Since there are no models which predict the influence of pupil size on threshold contrasts for the identification of letters, we have tried to understand the role played by pupil size in our measurements from models developed for sine wave gratings detection. The issue of the frequency components in the Fourier spectrum of a letter directly involved in its recognition is still under investigation and has been the subject of considerable study (Majaj *et al.*, 2002 and references therein; Petkov and Westenberg, 2003). Therefore, the numbers assigned to the different sizes employed in this work (3, 10, 20, and 30 c deg^{-1}) may not be the most appropriate numbers, but certainly give an idea of low, medium and high spatial frequencies u and allow us to qualitatively compare theoretically predicted Δlog(CS) values with the experimental measurements.

Although more modern models exist (Watson and Ahumada, 2005) for the CSF, that from Barten (1999; pp. 27–40) has been selected because of its success in comparisons across a variety of experimental conditions. This model combines a $M_{opt}(u)$ (MTF of the eye) with a neural function which includes neural noise, photon noise, and lateral inhibition effects, as well as the influence of retinal illumination, other physical characteristics of the eye and of the test. All these parameters are known in our experiment, so the model can be easily applied.

A typical point of discussion in the last years was the functional nature of the ocular MTF. Three approaches are considered here. Barten (1999) himself proposes a Gaussian modulation transfer function resulting from the combination of different effects like the optics of the eye, stray light in the ocular media, diffusion in the retina and the discrete nature of photoreceptors. This functional dependence, combined with his neural function, has been proven to be a good predictor of the final CSF particularly in the high spatial frequency domain. Otherwise, a double-pass measurement method suggested by Artal and Navarro (1994) proposes a two parameter exponential function model for the ocular MTF. This yields very good fits in the low and intermediate spatial frequency domain. Their model, although based on measurements performed with monochromatic light, gives very similar results to others obtained with polychromatic light (Campbell and Gubisch, 1966). Thirdly, by combining data from psychophysical measurements with information from previous studies, Rovamo *et al.* (1998) proposed for the ocular MTF a functional dependence of the type:

$$M_{opt}(u) = \exp[-(u/u_c)^n], \tag{2}$$

where $u_c = (16.6–1.49d)$, $n = exp[(0.84/d)–0.318]$ and d is the pupil diameter in mm. We have combined each of these three different types of suggested $M_{opt}(u)$ functions with the neural function proposed by Barten (1999), and calculated the predicted Δlog(CS) values. In these calculations, the test and surround luminances, measured pupil sizes and test dimensions have been considered. These results, as well as our data shown in *Figure 4*, have been separately displayed in *Figure 6* as a function of log(L_s) for the four letter sizes.

The first remarkable point arising from *Figure 6* is the existence of an interesting and reasonably good agreement in the quantitative and functional influence of surround luminance on Δlog(CS) values between our measurements performed with contrast sensitivity letter charts, and theoretical predictions for sine wave grating detection. Our measurements are, in all cases, placed between some of the theoretical curves. With the exception of the predictions performed with a Gaussian MTF (Barten, 1999) for 3 and 10 c deg^{-1}, all calculations predict increments in contrast sensitivity when changing surround luminance from 1 to 100 cd m^{-2}; that is to say, models seem to show that the enhancement of retinal image quality due to the pupil constriction when surround luminance increases, is dominant over the loss of foveal retinal illuminance. In order to quantitatively compare our measurements with those calculations, for each spatial frequency and type of MTF considered, the standard deviation σ of the differences between our data and theoretical predictions have been calculated: these are shown in *Table 2* with the average and standard deviation for each type of MTF. For low spatial frequencies, the best agreement between our data and theoretical models is for that in which a two-parameter exponential function is considered for the modulation transfer function (Artal and Navarro, 1994). Otherwise, for the highest spatial

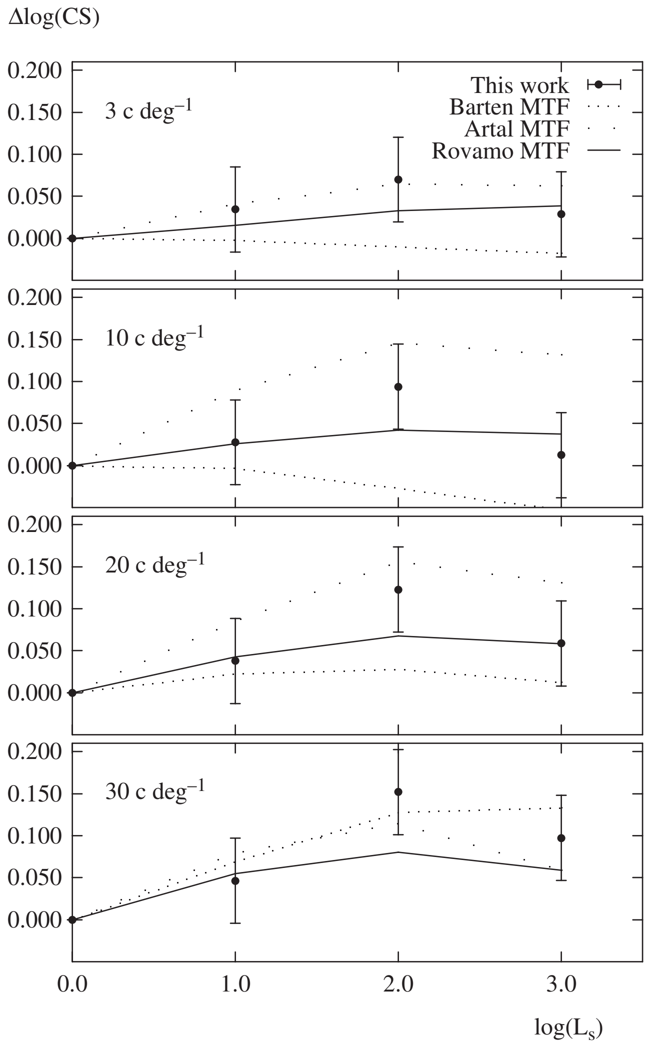

Figure 6. Comparison of our measured changes in the log(CS) values as a function of *log*(L_s) with theoretical predictions calculated by combining different MTFs with a typical neural function. From top to bottom, results for 3, 10, 20 and 30 c deg^{-1} are shown in the figure. Error bars are the same as those shown in *Figure 4*.

Table 2. Standard deviations (σ) of the differences between our measured Δlog(CS) values and the theoretical predictions for each fundamental spatial frequency (*u*) and type of MTF considered (see *Figure 6*)

***u* (c deg^{-1})**	**Barten (1999)**	**Artal and Navarro (1994)**	**Rovamo *et al.* (1998)**
3	0.099	0.035	0.043
10	0.143	0.144	0.057
20	0.107	0.093	0.055
30	0.049	0.063	0.082
Average σ	0.099	0.084	0.059

frequency tested, the best agreement is reached with a Gaussian MTF (Barten, 1999). This is in agreement with the analysis performed by Barten (1999) for the high spatial frequencies, and by Artal and Navarro (1994) for the low spatial frequencies, respectively. In the intermediate spatial frequency domain, the MTF dependence proposed by Rovamo *et al.* (1998) gives the smallest difference with our measurements. When looking at the average standard deviations, this last MTF functional dependency offers the best overall agreement with our data in the tested frequency interval.

Discussion

We have found a small, but measurable, influence of surround luminance on the shape of the letter contrast sensitivity function. This is seen to some extent in *Figure 3*, but is more clearly shown in *Figure 4*. This result is not completely new. Some previous experiments showed that an illuminated surround yielded contrast sensitivities higher than those obtained with a dark or an almost dark surround. Blommaert and Timmers (1987) performed an experiment with letters from 18 to 42 c deg^{-1} fundamental spatial frequency, but with only two observers, and found that an adapting field of 150 cd m^{-2} generated higher CS values than an adapting field of 0.9 cd m^{-2}. Cox *et al.* (1999) found significantly higher letter CS values for surround luminances of 900 cd m^{-2} than for 5.6, 9.0 or 30 cd m^{-2}. Their experiment was performed with a Pelli–Robson test at a luminance of 160 cd m^{-2} and with only four individuals. These differences appeared at viewing distances of 4 m (fundamental spatial frequency of 3.49 c deg^{-1} approximately), but not at 1 m (fundamental spatial frequency of 0.87 c deg^{-1}). The differences also disappeared when using an artificial pupil. It is important to note that the results obtained by these authors for sine-wave gratings were the opposite. In an experiment performed with the same type of test and 30 individuals, but with a fundamental spatial frequency of 10.9 c deg^{-1} and a test luminance of 200 cd m^{-2},Vizmanos *et al.* (2004) found significantly higher CS values with a surround luminance of 150 cd m^{-2} than for 0.5 cd m^{-2}. Finally Khanani *et al.* (2004) performed measurements of contrast sensitivities with Sloan letters displayed on a monitor whose mean luminance was 95 cd m^{-2}. The spatial frequencies tested were 8, 12 and 20 c deg^{-1} and the ambient lighting conditions employed were both a typically illuminated room with fluorescent ceiling panel light, and an almost dark room. They found that the illuminated surround produced contrast sensitivities which were higher than those measured under dark surround conditions. It appears that there is a real need for standardization of the illumination in ophthalmic consulting rooms in order to obtain illumination conditions in which contrast sensitivity remains invariant. The existence of these directives would also help to make the contrast sensitivity a more helpful tool in clinical assessment and diagnostics by increasing the confidence among practitioners.

The second interesting point is the different influence of surround luminance on different letter sizes, at least in quantitative terms. *Figure 4* shows this and also the statistically significant interaction found between surround luminance and fundamental spatial frequency as explained above. This influence is small for the larger letter sizes (3 and 10 c deg^{-1}) but is clearly more important for 20 c deg^{-1} and particularly for 30 c deg^{-1} letter sizes. This result was previously observed by Blommaert and Timmers (1987) and by Khanani *et al.* (2004) but they could not provide any information concerning the functional influence of surround luminance for each letter size (spatial frequency), because these two studies were performed with only two surround lighting conditions: non-illuminated and illuminated surround. The current study extends this earlier work, and from *Figures 3 and 4* it can be seen that this functional influence is very similar for the whole range of estimated fundamental spatial frequencies considered. For a test luminance of 200 cd m^{-2}, letter contrast sensitivity always increases as surround luminance increases from 1 to 100 cd m^{-2} (0.5–50% of test luminance) and decreases for surround luminance of 1000 cd m^{-2}. The *y*-axes in *Figure 4* represent differences in log(CS) values, so any possible influence of the scoring and stopping procedure in CS evaluation should be eliminated when calculating these differences: it certainly does not explain these systematic trends (Elliott *et al.*, 1990, 1991; Arditi, 2005).

Although the pupil size variation may be considered a good explanation for the measured increments in the Δlog(CS) values when surround luminance increases from 1 to 100 cd m^{-2}, it is difficult to consider it as a valid explanation of the decrease observed in the letter contrast sensitivity function when surround luminance increases from 100 to 1000 cd m^{-2}. A look to pupil sizes and foveal retinal illuminances in *Table 1* suggests this. When pupil size goes from 3.0 to 2.5 mm (far from the limit where diffraction effects should be considered), all proposed MTFs increase slightly in the whole frequency range with the exception of the two-parameter exponential model in the range of 25–30 c deg^{-1} which shows a small decrease. This pupil change yields a foveal retinal illuminance decrement of around 30%. This small reduction in the retinal illumination should not explain such important decrease observed in the Δlog(CS) values for all frequencies. In fact, a Gaussian MTF model, which provides the best agreement with our measurements for high spatial frequencies, predicts an increment in the Δlog(CS) for 30 c deg^{-1} in this range of surround luminance. Otherwise, the two-parameter exponential functions model, which provides the best agreement with our measurements for low spatial frequencies, predicts no change in Δlog(CS) for 3 c deg^{-1}. In the intermediate spatial frequencies domain, the MTF proposed by Rovamo *et al.* (1998) combined with the neural function proposed by Barten (1999) certainly predicts a small decrement but this is clearly lower than the one measured. Optical aberrations or ocular misalignments effects can not explain this result, since most of these decrease as pupil size does. Different influences of surround luminance due to different colour temperatures, which appear in this work, might explain part of these discrepancies, but no previous information exists in the literature concerning this point. Therefore, it is difficult to quantify its influence.

Other optical effects, like stray light or glare, might also be the origin of these decrements. Glare produces a veiling luminance which increments the luminance at the retina by a factor which depends on the L_s-values and which is indicated in the fifth column of *Table 1*. This factor is the same by which the perceived contrast is reduced in relation to the original test contrast. By applying this argument to the threshold contrasts perceived, the effect of increasing surround luminance should be a decrease in the measured log(CS) values. In this way, when surround luminance increases from 1 to 100 cd m^{-2} (i.e. when surround luminance L_s is below test luminance L_t), log(CS) should reduce by log(1.030/1.011) = 0.008 log units. Obviously, this is undetectable and non-comparable with the benefit produced by the pupil miosis (pupil diameter decreases from 4.7 to 3.0 mm). Conversely, when surround luminance goes above the test luminance (200 cd m^{-2}), i.e. increases from 100 to 1000 cd m^{-2}, pupil size does not change too much (3.0 to 2.5 mm) but the threshold contrast decreases by a factor (1.204/1.030) = 1.169 whose log-value is 0.068. The average decrement and standard deviation observed in log(CS) (see *Figure 4*) for the four targeted spatial frequencies considered in this experiment are 0.063 and 0.015 log units, respectively. This good agreement between calculated and observed decrements in threshold contrast makes us suggest that glare is responsible for the decrease in letter CS for high surround luminances.

It is well known that an increment in the adaptation luminance produces an increment in contrast sensitivity (Van Nes and Bouman, 1967). Since the task involved in this experiment is foveal, local adaptation plays an important role in the final results. Changes in surround luminance produce not only changes in the general adaptation of the visual system, but also an increment in the light arriving at the fovea due to veiling luminance. When L_s goes from 1 to 100 cd m^{-2}, the increment in foveal luminance due to veiling luminance is lower than 3%, a negligible quantity too small to justify the increment observed in contrast sensitivity. This increment is more reasonably explained by the increment in the optical quality of the retinal image produced by pupil constriction. When L_s goes from 100 to 1000 cd m^{-2}, the increment of light arriving at the fovea due to veiling luminance is $>20\%$. However, our results show in this case a systematic decrease in letter CS for all letter sizes considered. Although the increment in the adaptation luminance may result in some improvement in contrast sensitivity, it is evident from our results that the opposite effect of L_v on contrast sensitivity by reducing contrast in the retinal image more correctly explains the results found in this work. Glare is again necessary to explain this effect.

Our results are in apparent contradiction to those obtained by Cox *et al.* (1999) with letter charts. These authors found continuously increasing CS values as surround luminance increased from 5.6 to 900 cd m^{-2}, with a test luminance of 160 cd m^{-2}. At the frequency of 3.49 c deg^{-1}, the test and surround subtended approximately 11 and 24 degrees, respectively in their experiment. As is seen in *Figure 4*, the maximum change observed in Δlog(CS) at 61 mm letter size (3 c deg^{-1}) in this experiment is only 0.07 log units (when L_s changes from 1 to 100 cd m^{-2}), and the visual field subtended by the surround is around 34 degrees. With these similar visual fields the effect of changing surround luminance on pupil size should be, according to Stanley and Davies (1995), very similar in the two experiments. However, the expected loss of log CS due to the veiling luminance in Cox *et al.*'s experiment when surround luminance increases from 100 to 900 cd m^{-2} is around 0.025 log units (Adrian and Topalova, 1991). Although not statistically significant, this effect is more or less guessed in their results when an artificial pupil was employed. We can conclude that the pupil miosis in their experiment should be dominant over the effects of a possible disability glare in the range from 100 to 900 cd m^{-2}.

In conclusion, the present study provides information about the quantitative influence of significant surround luminance changes on the letter contrast sensitivity function obtained for a typical test luminance, as well as of its functional dependence on this variable. The increasing MTF explains that these changes are mostly due to the pupil miosis produced when surround luminance increases, at least while this luminance stays below the test luminance. For higher surround luminances, other effects like glare explain adequately the observed decrease in contrast sensitivity. From a clinical point of view, it should be noted that this study was performed with young individuals, that is to say, the expected letter CS decrement for older people due to a high surround luminance would be more significant. These observations reinforce the need for standardization of directives for illumination conditions in the clinical offices. These directives should consider that the best letter CS function is achieved for surround luminances below test luminance where pupil miosis produces the known optical benefit and glare does not reduce the retinal contrast.

Acknowledgements

The authors thank S. González for his collaboration in the experimental arrangement, and the Spanish Dirección General de Investigación Científica y Técnica (Ministerio de Educación y Ciencia) and the Consejería de Educación y Cultura de Castilla y León for their financial support under contracts No. FIS2005/05451, VA021A05 and VA090A08. Dr J. A. Aparicio wants to express his personal acknowledgment to the Organización Nacional de Ciegos de España (ONCE) for help.

References

Abrahamsson, M. and Sjöstrand, J. (1986) Impairment of contrast sensitivity function (CSF) as a measure of disability glare. *Invest. Ophthalmol. Vis. Sci.* **27,** 1131–1136.

Adrian, W. and Topalova, R. (1991). Transient adaptation process. A model to predict its effects on vision. In: *Proceedings of the CIE 22nd Session 2*. pp. 121–133.

Akutsu, H., Bedell, H. E. and Patel, S. S. (2000) Recognition thresholds for letters with simulated dioptric blur. *Optom. Vis. Sci.* **77,** 524–530.

American National Standards Institute (ANSI) (2004). *ANSI Z80.21-1992 (R2004)–General Purpose Clinical Visual Acuity Charts*. Optical Laboratories Association, ANSI, New York, NY, USA.

Arditi, A. (2005) Improving the design of the letter contrast sensitivity test. *Invest. Ophthalmol. Vis. Sci.* **46,** 2225–2229.

Artal, P. and Navarro, R. (1994) Monochromatic modulation transfer function of the human eye for different pupil diameters: an analytical expression. *J. Opt. Soc. Am. A Opt. Image. Sci. Vis.* **11,** 246–249.

Atchison, D. A., Woods, R. L. and Bradley, A. (1998) Predicting the effects of optical defocus on human contrast sensitivity. *J. Opt. Soc. Am. A Opt. Image. Sci. Vis.* **15,** 2536–2544.

Bach, M. (1996) The Freiburg Visual Acuity test – automatic measurement of visual acuity. *Optom. Vis. Sci.* **73,** 49–53.

Bach, M., Wesemann, W., Kolling, G., Bühren, J., Krastel, H. and Schiefer, U. (2008) Photopic contrast sensitivity; Local contrast perception (Photopisches Kontrastsehen; Örtliche Kontrastempfindlichkeit). *Ophthalmologe* **105,** 46–59.

Banks, M. S., Geisler, W. S. and Bennett, P. J. (1987) The physical limits of grating visibility. *Vision Res.* **27,** 1915–1924.

Barten, P. G. J. (1999). *Contrast Sensitivity of the Human Eye and Its Effects on Image Quality*. SPIE Optical Engineering Press, Bellingham, WA, USA.

Blackwell, H. R. (1946) Contrast threshold of the human eye. *J. Opt. Soc. Am.* **36,** 624–643.

Blommaert, F. J. J. and Timmers, H. (1987) Letter recognition at low contrast levels: effects of letter size. *Perception* **16,** 421–432.

Brown, S. M., Khanani, A. M. and Xu, K. T. (2004) Day to day variability of the dark-adapted pupil diameter. *J. Cataract Refract. Surg.* **30,** 639–644.

Campbell, F. W. and Gubisch, R. W. (1966) Optical quality of the human eye. *J. Physiol.* **186,** 558–578.

Coletta, N. J. and Sharma, V. (1995) Effects of luminance and spatial noise on interferometric contrast sensitivity. *J. Opt. Soc. Am.* **12,** 2244–2251.

Colombo, E., Issolio, L., Santillán, J. and Aguirre, R. (2009) What characteristics a clinical CSF system has to have? *Optica Applicata* **39,** 415–428.

Cox, M. J., Norman, J. H. and Norman, P. (1999) The effect of surround luminance on meaurements of contrast sensitivity. *Ophthalmic Physiol. Opt.* **19,** 401–414.

Elliott, D. B., Whitaker, D. and Bonette, L. (1990) Differences in the legibility of letters at contrast threshold using the Pelli–Robson chart. *Ophthalm. Physiol. Opt.* **10,** 323–326.

Elliott, D. B., Bullimore, M. A. and Bonette, L. (1991) Improving the reliability of the Pelli-Robson contrast sensitivity test. *Clin. Vis. Sci.* **6,** 471–475.

Higgins, K. E., Arditi, A. and Knoblauch, K. (1996) Detection and identification of mirror-image letter pairs in central and peripheral vision. *Vision Res.* **36,** 331–337.

International Organization for Standardization (ISO) (1996) ISO:8596. *Ophthalmic Optics -Visual Acuity Testing -Standard Optotype and its Presentation.* AENOR, Madrid, pp. 1–11.

Iwasaki, T. and Tawara, A. (2002) Effects of viewing distance on accommodative and pupillary responses following a three-dimensional task. *Ophthalm. Physiol. Opt.* **22,** 113–118.

Jansonius, N. M. and Kooijman, A. C. (1997) The effect of defocus on edge contrast sensitivity. *Ophthalmic Physiol. Opt.* **17,** 128–132.

Kelly, D. H. (1977) Visual contrast sensitivity. *Opt Acta (Lond)* **24,** 107–129.

Khanani, A. M., Brown, S. M. and Xu, K. T. (2004) Normal values for a clinical test of letter-recognition contrast thresholds. *J. Cataract Refract. Surg.* **30,** 2377–2382.

Legge, G. E., Pelli, D. G., Rubin, G. S. and Schleske, M. M. (1985) Psychophysics of reading-I. Normal Vision. *Vision Res.* **25,** 239–252.

Long, G. M. and Penn, D. L. (1987) Normative contrast sensitivity functions: the problem of comparison. *Am J. Optom. Physiol. Opt.* **64,** 131–135.

Lythgoe, R. J. (1932) The measurement of visual acuity. *Med. Res. Counc. Spec. Res. Ser* **173,** 1–85.

Majaj, N. J., Pelli, D. G., Kurshan, P. and Palomares, M. (2002) The role of spatial frequency channels in letter identification. *Vision Res.* **42,** 1165–1184.

National Academy of Science, National Research Council (NAS-NRC). Committee on Vision. (1983). Recommended standard procedures for the clinical measurement and specification of visual acuity. Report of working group 39. *Adv. Ophthalmol.* **41,** 103–148.

Patel, A. S. (1966) Spatial resolution by the human visual system. The effect of mean retinal illuminance. *J. Opt. Soc. Am.* **56,** 689–694.

Pelli, D. G., Robson, J. G. and Wilkins, A. J. (1988) The design of a new letter chart for measuring contrast sensitivity. *Clin. Vis. Sci.* **2,** 187–199.

Petkov, N. and Westenberg, M. A. (2003) Suppression of contour perception by band-limited noise and its relation to nonclassical receptive field inhibition. *Biol. Cybern.* **88,** 236–246.

Puell, M. C., Palomo, C., Sánchez-Ramos, C. and Villena, C. (2004) Normal values for photopic and mesopic letter contrast sensitivity. *J. Refract. Surg.* **20,** 484–488.

Rabin, J. (1994) Luminance effects on visual acuity and small letter contrast sensitivity. *Optom. Vis. Sci.* **71,** 685–688.

Rabin, J. (1995) Two eyes are better than one: binocular enhancement in the contrast domain. *Ophthalmic Physiol. Opt.* **15,** 45–48.

Radhakrishnan, H., Pardhan, S., Calver, R. I. and O'Leary, D. J. (2004) Effect of positive and negative defocus on contrast sensitivity in myopes and nonmyopes. *Vision Res.* **44,** 1869–1878.

Regan, D. and Neima, D. (1983) Low-contrast letter charts as a test of visual function. *Ophthalmology* **90,** 1192–1200.

Rovamo, J., Kukkonen, H. and Mustonen, J. (1998) Foveal optical modulation transfer function of the human eye at various pupil sizes. *J. Opt. Soc. Am. A Opt. Image. Sci. Vis.* **15,** 2504–2513.

Scialfa, C. T., Tyrell, R. A., Garvey, P. M., Deering, L. M., Leibowitz, H. W. and Goebel, C. C. (1988) Age differences in Vistech near contrast sensitivity. *Am. J. Optom. Physiol. Opt.* **65,** 951–956.

Sheedy, J. E., Bailey, I. L. and Raasch, T. W. (1984) Visual acuity and chart luminance. *Am. J. Optom. Physiol. Opt.* **61,** 595–600.

Shlaer, S. (1937) The relation between visual acuity and illumination. *J. Gen. Physiol.* **21,** 165–188.

Sloan, L. L. (1951) Measurement of visual acuity: a critical review. *Arch. Ophthalmol.* **45,** 704–725.

Stanley, P. A. and Davies, A. K. (1995) The effect of field of view size on steady-state pupil diameter. *Ophthalmic Physiol. Opt.* **15,** 601–603.

Strang, N. C., Atchison, D. A. and Woods, R. L. (1999) Effects of defocus and pupil size on human contrast sensitivity. *Ophthalmic Physiol. Opt.* **19,** 415–426.

Strasburger, H. (1997) R_Contrast: rapid measurement of recognition contrast thresholds. *Spat. Vis.* **10,** 495–498.

Strasburger, H. and Rentschler, I. (1996) Contrast-dependent dissociation of visual recognition and detection field. *Eur. J. Neurosci.* **8,** 1787–1791.

Strasburger, H., Harvey, L. O. Jr and Rentschler, I. (1991) Contrast thresholds for identification of numeric characters in direct and excentric view. *Percept Psychophys* **49,** 495–508.

Strasburger, H., Rentschler, I. and Harvey, L. O. Jr (1994) Cortical magnification theory fails to predict visual recognition. *Eur. J. Neurosci.* **6,** 1583–1588.

Sucs, F. E. and Uvijls, A. (1992) Contrast sensitivity in retinitis pigmentosa at different luminance levels. *Clin. Vis. Sci.* **7,** 147–151.

de Valois, R. L., Morgan, H. and Snodderly, D. M. (1974) Psychophysical studies of the monkey vision III Spatial luminance contrast sensitivity tests of macaque and human observers. *Vision Res*. **14,** 75–81.

Van Nes, F. L. and Bouman, M. A. (1967) Spatial Modulation Transfer in the Human Eye. *J Opt. Soc. Am*. **57,** 401–406.

Vizmanos, J. G., de la Fuente, I., Matesanz, B. M. and Aparicio, J. A. (2004) Influence of surround illumination on pupil size and contrast sensitivity. *Ophthalmic Physiol. Opt*. **24,** 464–468.

Watson, A. B. and Ahumada, A. J. Jr (2005) A standard model for foveal detection of spatial contrast. *J. Vis*. **5,** 717–740.

Whitaker, D., Elliott, D. B. and Steen, R. (1994) Confirmation of the validity of the psychophysical light scattering factor. *Invest. Ophthalmol. Vis. Sci*. **35,** 317–321.

Woods, R. L., Strang, N. C. and Atchison, D. A. (2000) Measuring contrast sensitivity with inappropiate optical correction. *Ophthalmic Physiol. Opt*. **20,** 442–451.