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Light adaptation in letter contrast sensitivity: The influence of optical and neural mechanisms

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This work discusses the relative significance of optical and neural mechanisms in letter contrast sensitivity under different conditions of environmental lighting. A study was carried out on 26 eyes with normal ocular health. Sixteen lighting conditions were obtained by combining different test luminances (from 10 cd/m^2 to 600 cd/m^2) and surround luminances (from 1 cd/m^2 to 600 cd/m^2). The results reveal a significant influence of optical factors (pupil size variations and glare effects) on contrast sensitivity when surround luminance changes, and a dominance of neural effects when test luminance changes. Furthermore, test size and illumination conditions are identified for which letter threshold contrasts are not sensitive to surround luminance changes.

1. Introduction

Contrast sensitivity (CS) is a visual function that provides valuable information about the spatial response of the visual system. It is known that this depends on different factors: optical and neuro-physiological. Among the first, the ocular optics establish a limit to the quality of retinal image. The modulation transfer function (MTF) of the eye shows contrast reduction at each spatial frequency. The existence of strong light sources in the observer's visual field can also produce a reduction in the contrast of the retinal image, diminishing both the visibility of the object and the CS of the visual system. At scotopic and mesopic light levels, it is known that the main limitations of human performance are set by the neural system.[1,2] Very recently, Jing-Jing and Zhao-Qi have evaluated the influence of the luminance at photopic levels (15 cd/m^2, 210 cd/m^2 and 310 cd/m^2) on the neural mechanism.[3] For their experimental conditions, the increase of luminance produces a change in the gain of the neural system lower than that produced by the optical system, especially at high spatial frequencies.

Most of what we know about the optical and neural effects is based on studies that have been carried out by using detection stimuli (spots, Gabor patches or sinusoidal gratings). From the oldest to the most modern work, a reduction of the threshold contrast with increasing luminance in sinusoidal

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gratings has been observed.[4,5] Knowledge is much less developed in tests for the recognition of threshold contrast letters, in spite of the relevance of these tests to evaluating our visual health in daily life. Puell *et al.*[6] measured the CS with the Pelli-Robson test for a wide range of ages in dark surround conditions, for photopic and mesopic test luminances L_T (this is the term that will be used from now on to designate the luminance of the visual field immediately adjacent to the optotype).

The literature also offers us works in which test luminance is kept steady (80–300 cd/m^2) and the surround luminance L_S is varied (L_S is the term we will use from now on to designate the luminance of the visual zone external to the optotype card). In this way, Blommaert and Timmers,[7] Khanani *et al.*[8] and Vizmanos *et al.*[9] used a test luminance fixed at 90 cd/m^2, 95 cd/m^2 and 200 cd/m^2, respectively, always under two conditions of surround luminance, photopic and mesopic. Cox *et al.*[10] widened the range of surround luminances, and found a tendency for the CS to increase when the surround luminance got bigger. Recently, we analysed the quantitative and functional influence of the luminance of the surround area on the CS of letters of different angular sizes,[11] the effect being slightly more significant for small letters. In that work it was demonstrated that, for a fixed test luminance of 200 cd/m^2, the highest log CS value was reached when the surround luminance was very close to the test luminance used in the experiment.

However, the interaction between the two variables L_T and L_S and its effect on letter CS has still not been analysed in depth. In fact, the first important objective of this work is precisely that: To evaluate this interaction and to correlate it to the optical and physiological aspects that influence CS. For this reason, our starting point will be the classical models of veil luminance, MTF and the neural function for sinusoidal gratings, as a first approach to letter CS. Finally, although illumination has a significant influence on CS and this is a visual function directly related with our ocular health, there are no lighting standards for ophthalmic offices where this variable is measured. The second objective of this work is to determine some experimental conditions under which letter CS remains constant under changes in the surround luminance. This situation is, from a practical point of view, very convenient because it represents an ideal framework in clinical practice since the repeatability and reliability of the results is better guaranteed. In fact, this lack of standardisation in lighting conditions in an ophthalmic office has been one of the most serious obstacles to the utilisation of CS in ophthalmology.

The results of this work have been obtained from a study in which we have determined letter CS in 16 different conditions of environmental lighting. For L_T ranges between 10 cd/m^2 and 600 cd/m^2 and of L_S ranges between 1 cd/m^2 and 600 cd/m^2, we analysed which aspects (optical or neural) and to what degree they determine the measured variations in the CS.

2. Materials and methods

2.1. Subjects

The tenets of the Declaration of Helsinki were followed. Eighteen subjects (26 eyes) were included, eleven were female and seven were male. The average and standard deviation of age was 22.8 ± 2.5 years old. Only healthy eyes, without media opacities and with an astigmatism less than or equal to 1.50 D were included. Consumers of any kind of medicine for several days prior to refraction or measurements were also rejected. Candidates who were users of contact lenses were asked not to use them for at least two days before the refraction and the CS measurements. All subjects, including the emmetropic and the users of contact lenses, were compensated with ophthalmic lenses to prevent differences in the results of CS due to this factor.[12] All eyes with monocular visual acuity values worse than −0.10 log MAR with their best optical correction were also rejected. The monocular visual acuities of our subjects ranged from −0.10 log MAR to −0.30 log MAR (1.3–2.0 decimal). No attempt was made to influence their natural pupil size.

2.2. Experimental arrangement

An exhaustive description of the experimental set-up has been previously published.[11,13] The subject was placed in front of a white cork wall subtending 33.8°, which will be called the surround from now on. A hole in its centre, subtending 3.8°, will be called test. The test area was lit by four 50 W halogen incandescent lamps controlled by independent stabilised power supplies. These lamps provided a uniform and constant test luminance L_T, whose variation was less than 2% of its average. The surround was lit by eight 300 W halogen incandescent lamps connected to a variable transformer. In these conditions, the cork wall acted as a light source with luminance inhomogeneities less than 15% of the average value. All lamps were turned on for 60 minutes prior to any measurement or calibration in order to stabilise.

All luminances were measured with a Spectra Pritchard model 1980A luminance meter. The selected L_T values for the measurements in this work were 10 cd/m^2, 80 cd/m^2, 200 cd/m^2 and 600 cd/m^2. The first of these corresponds to a low photopic luminance close to the limit with the mesopic range. The second and the third of these correspond to the lower limit and mean values, respectively, of the range used for visual acuity measurements as recommended by international standards.[14–16] The last of these was chosen because it represents a luminance much higher than that usually found in the clinical practice. Surround luminances of 1 cd/m^2, 10 cd/m^2, 200 cd/m^2 and 600 cd/m^2 were used. These values represent different lighting conditions that cover most of those that can be found in ophthalmic offices. These test and surround luminance values were achieved by changing the current in the stabilised power supplies or the output voltage of the variable transformer. These variations certainly generate changes in the spectral composition of light that, in principle, could influence the results of the measurements of visual acuity and CS.[17–19] However, in a previous work an additional study allowed us to discard this possibility in the experimental conditions employed in this work.[13] Pupil sizes were measured with an infrared pupilometer.[11] The ratio between the standard deviations and mean values were always lower than 10%.

A test chart based on the Pelli-Robson design was made.[20] It consisted of three sheets of paper with 16 triplets each. In order to avoid memory effects during measurements, four versions of each target were made. In each version, letters corresponding to the same contrast were different. Each chart contained square letters of 6.1 mm side, which subtended 4 min arc at a subject-to-chart distance of 5.2 m. These small letter CS tests have been shown to be particularly sensitive to changes in lighting conditions. Grey shades were chosen in such a way that Weber contrast decreases in steps of 0.024 log units between consecutive triplets. This step is six times less than that found in most of commercial CS targets. All details describing the design and fabrication of the optotypes and targets have already been described.[11] Experimental log contrast sensitivities follow a linear trend with a correlation coefficient $R^2 = 0.997$.

2.3. Procedure

The procedure employed was the following. Monocular CS measurements were made with a natural pupil so as to reproduce, as much as possible, the procedures used in clinical offices. Sixteen CS measurements were performed for each eye. They correspond to all combinations of the four test luminances and the four surround luminances. The order of measurements was randomised for different eyes. Subjects were asked to read from the top of the chart and were encouraged to guess the letters even when they were not clear. CS was recorded from the last group of letters in which two out of three letters were identified correctly. Prior to each trial, 5 minutes were allowed for the observers to adapt to the lighting conditions. This is considered enough time to elicit maximum pupil dilation for each specific lighting condition. The whole set of measurements for each observer took approximately 3 hours. No attempt was made to alter natural pupil size. It is important to note that, at a 5.2 m observer-to-target distance and for stimuli subtending 4 min arc the influence of head movements on the observer's performance is negligible.

For 10 eyes, pupil size measurements were performed under the 16 illumination conditions considered here. Three minutes were allowed for adaptation to each of the luminance conditions. Five pupil camera recordings were made during each exposure. Pupil diameters were extracted from these records and the average diameter *d* was calculated. The pupil and the letter CS measurements were made in different sessions.

3. Results

3.1. Pupil size

The mean pupil diameters of 10 eyes as a function of log surround and log test luminances are shown in Figure 1(a) and (b), respectively. Error bars define the 95% confidence intervals. The upper figure shows a decrease in the pupil diameter as log L_S increases, reaching a minimum value close to 3.0 mm for $L_S = 600\,\text{cd/m}^2$ and all test luminances, far from the values where diffraction effects should be considered. From these results, it is possible to conclude that there is a very significant variation of the pupil diameter when the environmental conditions of luminance are changed, from 5.9 ± 0.4 mm at low luminances to 2.95 ± 0.3 mm in conditions of high luminance. Furthermore, the pupil diameter seems to be more conditioned by the surround luminance (Figure 1(a)) than by test luminance (Figure 1(b)). This can be explained if we consider that, in our experiment, the solid angle subtended by the test as seen from the observer is around one hundredth of that subtended by the surround. In these conditions, luminous flux variations entering the pupil are mostly conditioned by surround luminance changes, the changes in test luminance only being capable of influencing the pupil size under dark surround conditions. It is clear that other sizes of angular fields of test and surround may make different contributions to the pupil variation.[21]

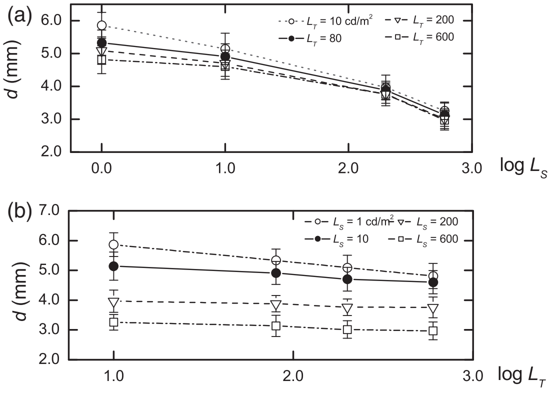

Figure 1 Average pupil diameters for the different illumination conditions, (a) as a function of log L_S, (b) as a function of log L_T. Luminances are always expressed in cd/m^2. Error bars define the 95% confidence interval

3.2. Contrast sensitivity

The average log CS values of the 26 eyes considered and their variation with the test and surround luminances, always in logarithmic units, are shown in Figure 2. It can be seen that, for a letter size of 4 min arc the logarithm of CS depends as much on the test luminance as on its close surround luminance. Its value can vary practically by a factor of three depending only on the environmental lighting conditions. It can also be observed that, in general, log CS seems to be more influenced by L_T than by L_S, the opposite of the behaviour observed in the pupil diameter.

From a statistical point of view, the 16 measurements performed on each eye cannot be considered as independent events. Each observer has a different visual acuity and observers with a higher visual acuity are known to exhibit letter CS which is higher than that of observers with a lower visual acuity. In this sense, part of the variability observed in measured data is due to the inherent visual features of each eye while another part comes from the random factors involved in any experiment. In order to consider these effects and to simultaneously analyse the influence of surround luminance L_S and test luminance L_T on the measured CS, a mixed-effects linear model was fitted to the experimental log CS data:

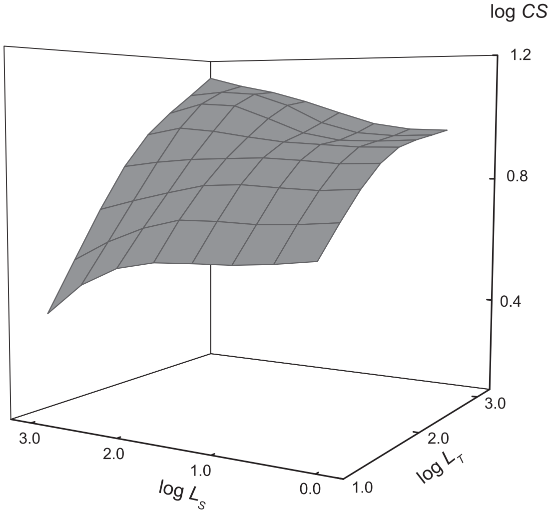

Figure 2 Simultaneous influence of log L_S and log L_T on log CS for an angular letter size of 4 min arc. Luminances are always expressed in cd/m^2

$$\log \mathrm{CS}_{iL_TL_S} = \alpha + \beta_{L_T} + \gamma_{L_S} + \delta_{L_T \leftrightarrow L_S} + b_i + \varepsilon_{iL_TL_S} \tag{1}$$

In this model, $\beta_{L_T}, \gamma_{L_S}$ and the interaction $\delta_{L_T \leftrightarrow L_S}$ are considered as fixed effects, b_i is a random effect associated with each individual and $\varepsilon_{iL_TL_S}$ corresponds to the residual error. The variance associated with the performance of each eye is 0.118 and the residual variance is 0.0038. The interaction fixed effect $\delta_{L_T \leftrightarrow L_S}$ is statistically significant ($p < 0.0001$). We can conclude therefore that, from a statistical point of view, the influence of test luminance on log CS is different for different surround luminances. Finally and according to recent studies, possible interocular correlation effects on our measurements were analysed.[22] In order to do that, the statistical analysis was repeated by including one eye per individual (18 eyes). Although residual variances slightly increased, neither mean log CS values nor the functional trends changed, the statistical conclusions being the same.

To be able to evaluate this influence in a quantitative way, we have drawn two sections of Figure 2 providing information from two different perspectives. In both, the error bars shown define the confidence intervals at 95%. The mean values obtained for the logarithm of CS are shown as a function of the logarithm of surround luminance, for the test luminances considered (Figure 3). This shows how the influence of L_S on log CS is very different for each test luminance, showing a behaviour that could be considered as opposite for $L_T = 600\,\mathrm{cd/m^2}$ and $L_T = 10\,\mathrm{cd/m^2}$. In the first case, log CS increases monotonically with L_S. In the

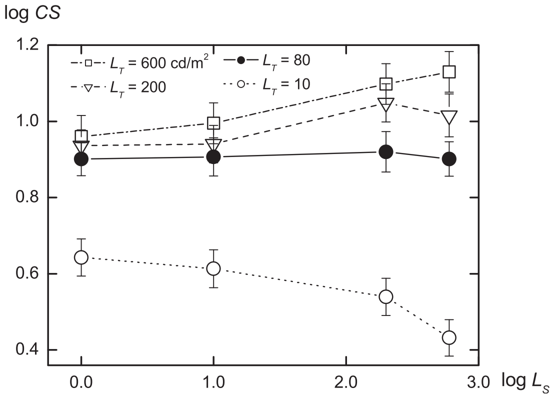

Figure 3 Log CS as a function of log L_S (in cd/m^2), for the four test luminances considered in this work

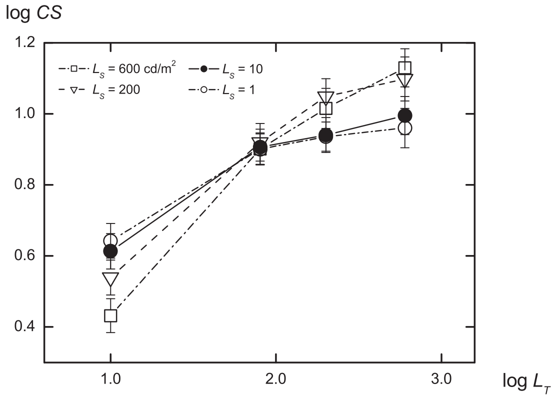

Figure 4 Log CS as a function of log L_T (in cd/m^2), for the four surround luminances considered in this work

second case, log CS reduces monotonically with increasing values of L_S. Another aspect worth noting in Figure 3 is that the maximum value of log CS for each L_T seems to be reached when the difference between the surround and the test luminances is minimal, as observed by Aparicio *et al.*,[11] but now extended to a significantly greater range of test luminances. Another important fact shown in Figure 3 is the behaviour of log CS for $L_T = 80\,\text{cd/m}^2$. In this case log CS seems to be insensitive to surround luminance changes.

In Figure 4, log CS is depicted as a function of log L_T for the four L_S values of the study. In addition to the well-known effect of improvement of CS with growing test luminance, Figure 4 confirms again that, for a test luminance of $80\,\text{cd/m}^2$ (the value recommended by the American standard of measurement of visual acuity) CS does not depend on the surround luminance. Figure 4 also helps evaluate the great variations that log CS may suffer, which goes from 0.40 ± 0.05 ($L_S = 600\,\text{cd/m}^2$, $L_T = 10\,\text{cd/m}^2$), to approximately 1.10 ± 0.05 units ($L_S = 600\,\text{cd/m}^2$, $L_T = 600\,\text{cd/m}^2$). Blackwell[4] found variations of the CS quantitatively similar to those found in our experiment, variations that are attributed classically to neural aspects of visual adaptation.

4. Discussion and conclusions

4.1. Model

As an approach to understanding the phenomena that influence the recognition of low contrast letters in very different environmental lighting conditions, we will use the classic models proposed for sinusoidal gratings. As a first step, and to be able to incorporate them in the analysis of our results, we have approximated the angular size of the letter (4 min arc) to a fundamental spatial frequency of 18 c/deg according to the conclusions reached by Majaj *et al.*[23]

$$\frac{f_{\text{channel}}}{10\,\text{c/deg}} = \left(\frac{f_{\text{stroke}}}{10\,\text{c/deg}}\right)^{2/3} \tag{2}$$

where f_{channel} corresponds to the frequency of the channel involved in the recognition of the letter (which will be identified as the spatial frequency u from now on) and f_{stroke} is the stroke frequency. The stroke frequency was defined by these authors as the average number of lines crossed by a slice through a letter at half height (1.6 in average for the normal Sloan alphabet), divided by the angular letter width.

For the purpose of verifying which part of the log CS variations could be explained by the ocular optics performance variations with environmental lighting conditions, we applied the analytic expression proposed by Artal and Navarro.[24] These authors, starting from measurements obtained by using the double-pass technique, proposed an empirical double exponential model for monochromatic light (Equation 3). In this equation A, B and C are parameters that depend on the pupil diameter d (A and B in degrees; C is adimensional):

$$\mathrm{MTF}(u) = (1 - C)\exp(-Au) + C\exp(-Bu) \tag{3}$$

This model of the MTF has been selected because it was obtained from foveal measurements carried out on subjects with similar age to ours (28 ± 2 years). In addition, this type of MTF provides, according to its authors, a particularly good result in the domain of mean spatial frequencies, such as those that have been considered in our work (18 c/deg).

In our experiment, the visual scene of the observer has been divided into two zones: test and surround. They can act as glare sources which induce an equivalent veiling luminance L_V on fovea that reduces the retinal image contrast and the CS. If the glare source geometrical distribution is similar to concentric rings located around the observation stimulus, the expression of Adrian and Topalova[25] can be applied to calculate this veiling luminance. This expression, valid for young subjects aged between 20 and 36 years old, can be written as:

$$L_V = 0.017608 \sum_{i=1}^{n} L_i(\ln\theta_{i+1} - \ln\theta_i) \tag{4}$$

L_V is the equivalent veiling luminance, L_i the mean luminance of each ring ($L_1 = L_T$, $L_2 = L_S$), expressed in cd/m^2 and θ the angular limits of these rings ($\theta_1 = 1^\circ$, $\theta_2 = 1.9^\circ$, $\theta_3 = 16.9^\circ$), expressed in degrees. For each experimental condition in our experiment, the contrast of the retinal image produced in the fovea of a subject is reduced by the factor $1 + L_V/L_T$.[11]

As for neural effects on low contrast letter recognition, our starting point will be the model proposed by Barten[26] which incorporates most of theoretical and experimental advances in neural contribution to CS function: Neural noise, photon noise, quantum efficiency, lateral inhibition effects, the influence of retinal illumination and other physical characteristics of the eye and of the test. Furthermore, it adapts very well to very different experimental conditions and it is very easily implemented in our case. This neural contribution is given by the equation:

$$\mathrm{NCSF}(u) = \frac{\mathrm{CSF}(u)}{\mathrm{MTF}_{\mathrm{opt}}(u)} = \frac{k}{\sqrt{\frac{2}{T}\left(\frac{1}{X_0^2} + \frac{1}{X_{\max}^2} + \frac{u^2}{N_{\max}^2}\right)\left(\frac{1}{\eta\rho E} + \frac{\Phi_0}{1 - e^{-(u/u_0)^2}}\right)}} \tag{5}$$

E being the retinal illuminance in trolands. A detailed explanation of the physical meaning of each of the parameters that take part in the previous expression can be found in the original reference. Typical values taken for these parameters in our work are shown in Table 1.

In order to analyse the individual contributions of each of the mentioned optical and neural effects on our measurements we have taken, as a hypothesis, that the variations observed experimentally in the logarithm of CS ($\Delta\log\,\mathrm{CS}(u)$) due to changes in the environmental lighting conditions, are the result of an additive combination of the optical and neural effects previously mentioned, according to the following expression:

$$\Delta \log \mathrm{CS}(u) = \Delta \log \mathrm{MTF}_{\mathrm{opt}}(u) + \Delta \log(1 + L_{\mathrm{V}}/L_{\mathrm{T}}) + \Delta \log \mathrm{NCSF}(u) \quad (6)$$

4.2. Effects of illumination changes on CS

In Figure 5, we have shown the experimental variations of the logarithm of CS ($\Delta \log \mathrm{CS}_{L_{\mathrm{S}}=1}$) with respect to its value for $L_{\mathrm{S}} = 1\,\mathrm{cd/m^2}$ (black squares) as a function of the log L_{S}, for each value of L_{T}. The error bars define the 95% confidence interval once the Bonferroni correction with $n = 12$ has been applied. In each graph, the contribution to the variation of CS of each one of the considered effects is also shown: variations of the MTF, of the veil contribution and of the neural effect as well as the combined effect of all of them.

Table 1 Typical values of the parameters that characterize the neural contrast sensitivity model of Barten[26]

$k = 3.0$	$N_{\mathrm{max}} = 15$ cycles	$\Phi_0 = 3 \times 10^{-8}$ s deg^2
$T = 0.1$ s	$\eta = 0.03$	$u_0 = 7$ cycles/deg
$X_{\mathrm{max}} = 12^{\circ}$	$\rho = 1.285 \times 10^6$ photons/(sg $\times$ deg^2 $\times$ troland)	

As can be seen in Figure 5 the combination of the three effects considered in the theoretical model comes close to the experimental data for the four values of L_{T} (10 cd/m^2, 80 cd/m^2, 200 cd/m^2 and 600 cd/m^2), producing an average deviation between the experimental and calculated values of 0.035 logarithmic units. As can be seen in the four panels, the two optical effects considered here act in opposite directions. On the one hand, as L_{S} increases, pupil diameter decreases (Figure 1(a)), the MTF increases and optical aberrations diminish producing an

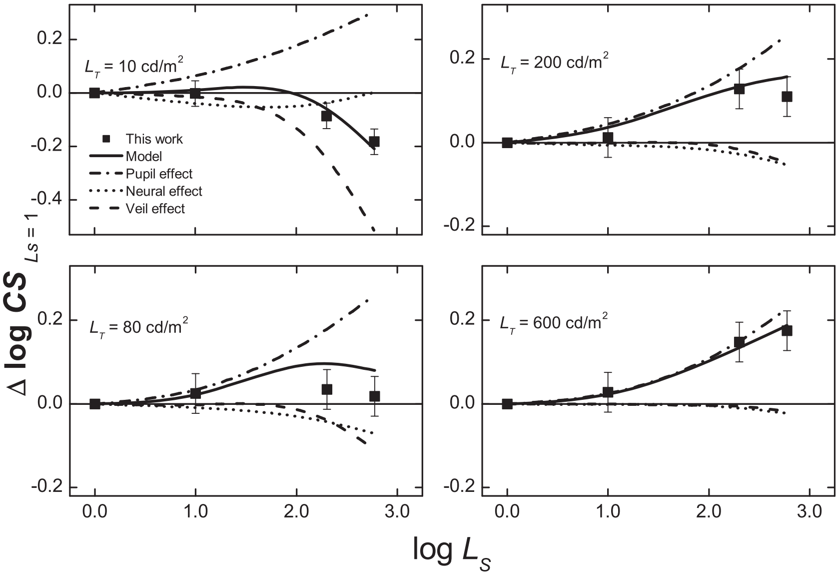

Figure 5 Comparison of our measured changes in log CS as a function of log L_{S} with theoretical predictions calculated by combining MTF (dotted and dashed line), veiling luminance (dashed line) and neural effects (dotted line) as well as the global theoretical effect (solid line). Each panel contains the information relative to a different L_{T} luminance

improvement in the retinal image quality. On the other hand, the growing effect of reduction of the retinal contrast as L_V increases, due to the increasing L_S, results in a decrease of the CS. This glare effect seems to be very dominant at $L_T = 10\,cd/m^2$ and explains why the increase of surround luminance results in such a significant decrease in $\Delta\log CS_{L_S=1}$ (around 0.20 logarithmic units, that is to say, eight groups of letters in the test that was designed for the experiment). The variation of the neural function is not very important in these conditions.

The experimental behaviour observed for the $\Delta\log CS_{L_S=1}$ in the case of $L_T = 600\,cd/m^2$ is contrary to the one described previously. A growing CS is associated with increasing surround luminance. The cause of this behaviour could be explained by the dominance of optical quality improvement over the glare effects. For $L_T = 600\,cd/m^2$, the effect of the increase of L_S over L_V is less significant because the factor $1 + L_V/L_T$ barely changes. The balance between the pupil miosis and the veiling luminance results in this case in a constant growth in CS. The effect of the neural component can again be ignored.

For $L_T = 200\,cd/m^2$, the CS grows when the surround luminance increases from $1\,cd/m^2$ (darkness) to $200\,cd/m^2$ but decreases slightly for higher values of L_S. This reproduces exactly the behaviour observed in previous work.[11] The most important contribution belongs to the optical MTF, while the veil and the neural factors are less significant.

For $L_T = 80\,cd/m^2$, we can observe how the increase of the surround luminance generates very small variations of CS; it could be said that this remains invariant under L_S changes between $1\,cd/m^2$ and $600\,cd/m^2$. In this situation, the negative effects of the components of glare and neural activity practically compensate the positive effect of pupil miosis.

The effect of the variations of the test luminance on the CS for every surround is shown in Figure 6. In this figure, we have depicted the variations of the logarithm of the CS with regards to its value for $L_T = 10\,cd/m^2$ ($\Delta\log CS_{L_T=10}$) as a function of log L_T for the four surround luminances. Once more, the error bars that are shown define the 95% confidence intervals once the Bonferroni correction for $n = 12$ has been carried out. In addition to the experimental data, the theoretical predictions are represented for the variation of the MTF (dashed and dotted line), the calculations of the reduction of contrast due to the variation of the veil effect (dashed line) and the calculations according to the Barten[26] model for the variation of the effects of the neural adaptation (dotted line). The global theoretical effect has been represented with a solid line.

As can be appreciated in Figure 6, the fit of the used model to the experimentally measured results is reasonably good (mean deviation = 0.083). We can see that, independent of the surround luminance, $\Delta\log CS_{L_T=10}$ always increases with increasing log L_T. When the contribution of each of the components of the model used is analysed independently, one can see the weak influence of MTF variations over the considered L_T values. This is explained, according to the results of Figure 1(b), by the minimal influence of the variations of the test luminance on the pupil diameter. With regard to the influence of the veil on the variations of the CS, it is interesting to observe how, for a fixed value of L_S, increasing values of L_T do not have too much influence on L_V but the CS reduction factor $1 + L_V/L_T$ is reduced noticeably, which represents an improvement of the CS, as can be seen in the four panels of Figure 6. The effect is, of course, more noticeable for high values of L_S ($200\,cd/m^2$ and $600\,cd/m^2$). The discrepancy observed at $L_S = 600\,cd/m^2$ is probably due to an over-estimation of L_V, an aspect which should be studied in greater detail.

Finally, the gain effect of the system due to neural adaptation becomes very important on

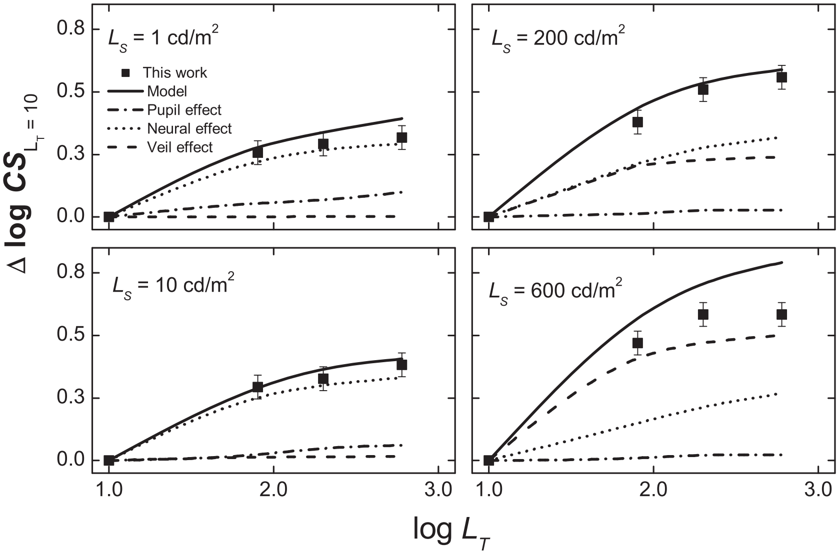

Figure 6 Comparison of our measured changes in log CS as a function of log L_T with theoretical predictions calculated by combining MTF (dotted and dashed line), veiling luminance (dashed line) and neural effects (dotted line) as well as the global theoretical effect (solid line). Each panel contains the information relative to a different L_S luminance

the measured variations of CS, especially for $L_S = 1$ and 10 cd/m^2, being the only significant factor that influences the results obtained in these cases. In our results, it can be seen how the neural contribution effect increases with L_T. A possible explanation could be the appearance of spatial summation effects contributing to the growth of CS with the mean foveal luminance. The measured quantities are quantitatively similar for all surround luminances, and also similar to the values given by Blackwell[4] in a detection experiment. The small discrepancies between the measurements and the model predictions might be mostly due to the fact that the theoretical models used, strictly speaking, do not correspond to the threshold contrast letter recognition, but to grating detection. We have assumed that the spatial frequency characteristic of the Sloan letters used is 18 c/deg in the Fourier spectrum.[23] However, other models seem to suggest different fundamental spatial differences.[27,28] The mean global deviation between the experimental and the calculated data is 0.057 logarithmic units. If we optimise this deviation by considering the fundamental spatial frequency as a free parameter, a smaller deviation (0.053 logarithmic units) is achieved for a spatial frequency of 23 c/deg. These minimal differences lead us to think that the model employed in this work predicts invariance in Δlog CS within the range of mean spatial frequencies. As far as the MTF used in the model is concerned,[24] this was obtained in an experiment using a double-pass technique with monochromatic light. It is important to point out that the results of that experiment are very similar to those obtained previously in the literature with polychromatic lights.[29]

We can conclude that, as a whole, the closeness between the experimental and calculated data corroborates the hypothesis initially stated, that is to say, the variations observed in log CS derived from changes in environmental lighting can be approximately considered as the additive contribution of the induced variations by the different optical and neural mechanisms. Furthermore, the conclusions reached for letters sized 4 min arc can be extended to other letter sizes. In fact, Aparicio *et al.*[11] proved that the effects of changing surround luminance on letter CS were functionally identical for letter sizes from 6.1 mm to 61 mm (from 4 min arc to 40 min arc in our experimental conditions). Finally, we should frame the results within the characteristics of the study performed. For example, it must be considered that young subjects participated in the experiment and it is known that both optical and neural mechanisms suffer significant deterioration with age.[6,30,31] In addition, the measurements taken certainly include wide ranges of test and surround luminances, but we should bear in mind that the results are also conditioned by factors such as the angular size of both visual fields, test and surround.

4.3. CS measurement in the clinical practice

It has been found that for a test luminance of 80 cd/m^2, CS for a letter sized 4 min arc, placed in a test area that subtends 3.8° from the observer, is certainly not the maximum but remains almost invariant against changes generated in the surround luminance encircling the test. Of course, other effects in the visual field of the observer like point glare sources or undesired reflections should be excluded. This luminance condition would be the one to be recommended for carrying out measurements of CS in the evaluation centres of the visual system, because of its easy technical implementation and because of the repeatability which would be added to the clinical results. In fact, it is curious to notice that, in spite of the validity of letter CS, both in clinical practice and in research,[32,33] standards of lighting for the carrying out of this visual test have not yet been defined in the literature although the demand for this standardisation does exist.[11,34] Cox *et al.*[10] suggested, in a work carried out with the Pelli-Robson test at 160 cd/m^2 and different conditions of L_S (5 cd/m^2, 6 cd/m^2, 9 cd/m^2, 30 cd/m^2 and 900 cd/m^2), that the standard of lighting for surround luminance in visual acuity (between 10% and 30% of card luminance), could be used as a luminance standard for CS tests. Their work did not pursue repeatability in the measurements but rather proved the influence of L_S on CS. Our results do not contradict theirs but actually complement them and provide working conditions easier to implement in ophthalmic offices. In addition, Durst *et al.*[35] have recently developed a lighting aid to produce homogenous luminance conditions in CS with the Pelli-Robson test. In this work, they recognise not only the need for a desired luminance but also the correct distribution of the same. They conclude that precision in the measurements is decisive for monitoring and for comparisons in multi-centre studies. Although both works employ a commercial test with a contrast step six times bigger than the one designed by us, both could be considered as complementary to our results.

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