Lighting Research and
Technology
http://lrt.sagepub.com/

The influence of spectral power distribution on contrast sensitivity

I Arranz, BM Matesanz, C de la Rosa, JA Menéndez, L Issolio, S Mar and JA Aparicio

Lighting Research and Technology published online 11 July 2011

DOI: 10.1177/1477153511402890

Lighting Res. Technol. 2011; **0**: 1–13

The influence of spectral power distribution on contrast sensitivity

I Arranz[a] PhD, **BM Matesanz**[a] PhD, **C de la Rosa**[a] MSc, **JA Menéndez**[b] PhD,
L Issolio[c] PhD, **S Mar**[a] PhD and **JA Aparicio**[a] PhD
[a]Departamento de Óptica, Universidad de Valladolid, P. Prado de la Magdalena s/n,
47071 Valladolid, Spain
[b]Departamento de Estadística e Investigación Operativa, Universidad de Valladolid,
P. Prado de la Magdalena s/n, 47071 Valladolid, Spain
[c]Departamento de Luminotecnia, Luz y Visión, Universidad Nacional de Tucumán,
– Instituto de Investigación en Luz, Ambiente y Visión, CONICET-UNT,
Avenida de Independencia 1800, 4000 Tucumán, Argentina

Received 12 November 2010; Revised 10 February 2011; Accepted 14 February 2011

The influence of lighting of different spectral power distribution on letter contrast sensitivity has been studied. The different spectral power distributions were obtained by filtering or dimming tungsten halogen lamps. Measurements were made on 20 young and healthy individuals (25 eyes) whose monocular contrast sensitivities were measured with a natural pupil. Sixteen combinations of test and surround luminance with high or low correlated colour temperatures were studied in such a way that the influence of test luminance, surround luminance or colour temperature of both visual fields could be independently studied. Both test luminance and surround luminance influenced contrast sensitivity but correlated colour temperature did not.

1. Introduction

Lighting plays a critical role in the offices of optometrists and ophthalmologists. Some typical and relevant human visual functions, like visual acuity (*VA*) and contrast sensitivity (*CS*), depend significantly on test and surround luminance. As a consequence, standards[1–3] have been written to define the lighting conditions under which visual acuity should be measured. Unfortunately, there are no standards concerning the proper ambient lighting for measuring contrast sensitivity, so the results obtained at different times or in different offices often are not repeatable or reproducible.

There are multiple studies that have shown the significant influence of test luminance[4–9] and surround luminance[10–15] on grating or letter contrast sensitivity. These studies have employed a wide variety of light sources (tungsten halogen lamps, fluorescent lamps, or even LEDs) but there is little knowledge of the influence of the spectral power distribution (SPD) on the measured contrast sensitivity. In some of these studies[11,14] surround luminance is changed by varying the electrical current through the light source. This might create uncertainty about whether the influence of surround lighting on contrast sensitivity is due to luminance of the surround or to the SPD of light from the surround. Moreover, as far as the commercial optotype projectors used in ophthalmic offices are concerned, they provide a wide range of test luminances and contrast conditions by varying the light output of what is usually a

---

Address for correspondence: Juan A. Aparicio, Departamento de Óptica, Universidad de Valladolid, P. Prado de la Magdalena s/n, 47071, Valladolid, Spain.
E-mail: apa@opt.uva.es

10.1177/1477153511402890

tungsten halogen lamp. In this case, test luminance and its SPD change simultaneously, making it impossible to determine if the contrast sensitivity changes observed in a patient are due to changes in test luminance or SPD or to changes in the patient's ocular health. Lamp ageing also produces changes in the light emitted by reducing the luminous flux and by changing the SPD of the light produced. Furthermore, video displays are beginning to play a significant role as chart projection systems in the assessment of visual capabilities. These CRT, LCD, and even LED-based video displays are likely to gradually replace the traditional chart projectors. In all these situations, contrast sensitivity is being measured using light of different SPD, which, in principle, makes the comparison of results and conclusions uncertain.

The existing literature on visual performance and SPD is scarce and sometimes controversial.[16–18] Boyce et al.[16] performed a study in the photopic range that assessed the performance of a visual task requiring the observer to identify the orientation of Landolt rings lit by fluorescent lamps at two different correlated colour temperatures (CCTs) (3000 K and 6500 K). They did not find any influence of SPD on the performance of the task. Berman et al.[17] performed a study in the photopic range in which the near visual acuity was measured for two fluorescent lamps of CCTs 3600 K and 5500 K. They found a significant difference in visual acuities between the two lamps. Fotios and Cheal[18] did not find any statistically significant differences in contrast sensitivity for high pressure sodium (CCT = 2000 K) and metal halide illumination (CCT = 2800 K) but they did find a significant increase in contrast sensitivity when low pressure sodium lamps were employed.

It can be concluded that luminance and SPD are parameters whose influence on visual acuity and contrast sensitivity should be independently analysed in order to complete the information necessary to configure future norms and standards on how the offices of optometrists and ophthalmologists should be lit.

2. Method

2.1 Apparatus

The experiment was carried out in a 6 × 3 × 3 m (length × width × height) room with white painted walls, isolated from outside light (Figure 1).[14] A white matte cork wall was built and a white matte square box (0.7 × 0.7 × 0.7 m) was placed behind it. The observers were seated 5.2 m away from the *CS* targets, which were placed at the back of the box and were visible through a 0.3 m diameter circular hole in the cork wall. The observer's visual field was divided in two parts: the circular hole which subtended 3.8 degrees from the observer, and the cork wall which subtended 33.8 degrees. From now on the central part will be called *test* and the outer will be called *surround*. The *test* was lit by four 50 W tungsten halogen lamps (Osram 64440 12 V 1098) controlled by independent stabilised power supplies. These lamps provided a homogenous and constant luminance (*test luminance* or L_T), the variation across the *test* area being less than 2% of the average. The surround was lit by eight 500 W tungsten halogen lamps (Osram 230 V Haloline 64701) connected to a variable transformer. In these conditions the cork wall acted as a light source whose luminance (*surround luminance* or L_S) showed variations of less than 15% of the average. All lamps were turned on for 60 minutes prior to any measurement or calibration in order to get good stabilisation. The matte finishes of the *test* and *surround* surfaces ensure there were no specular reflections visible to the observer.

All luminances were measured with a Spectra Pritchard model 1980A luminance meter. The maximum L_T-value measured was 598 cd/m^2, at a current of 4.2 A. The

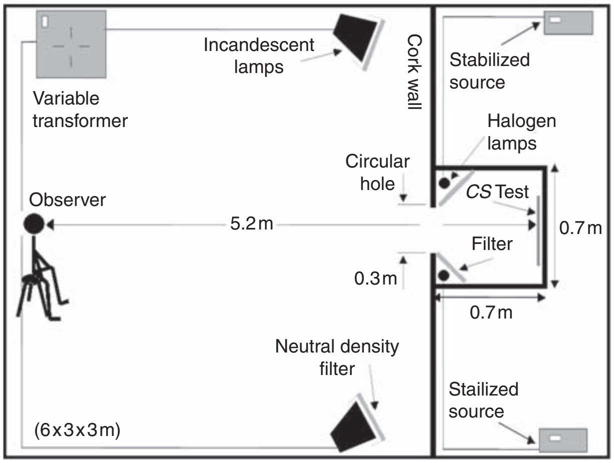

Figure 1 The arrangement of the experimental room

maximum L_S-value obtained was 986 cd/m^2, at an electrical output voltage on the variable transformer of 218 V. The selected L_T and L_S values for the measurements were 10 and 200 cd/m^2. The first corresponds to a luminance very close to the boundary between the photopic and mesopic.[19] Furthermore, although very different to luminances found in the visual field of patients in ophthalmic offices, this luminance value can be reached at a very low colour temperature and this will provide useful information about its influence on contrast sensitivity. The second value corresponds to the average of the recommended range in *test* luminances according to the international standards for visual acuity measurements.[1–3] These *test* and *surround* luminances were attained by two methods. First, by reducing the current of the stabilised power supplies or the output voltage in the variable transformer (condition N). Apart from reducing the luminance, this method causes a change in the SPD of the light emitted. Second, by placing neutral density filters (Gamcolour Inc) in front of the lamps luminances are reduced according to the filter's transmittance (Condition F).

Test and *surround* SPDs can be characterised by their CCT. Prior to any measurement on observers, the relative SPD was measured in the visible range for both *test* and *surround* lamps in the four conditions: 10 and 200 cd/m^2, obtained by the two procedures described above. Measurements were performed with a spectrometer equipped with a Jobin-Yvon HR1500 monochromator (2400 lines/mm holographic grating, 1.5 m focal length) and an Intensified Charge Coupled Device (ICCD) camera of Stanford Computer Optics Inc. These relative spectral radiance distributions were fitted to the corresponding blackbody emission functions and their CCTs were obtained from the fits. In all cases, the mean deviation of the experimental values relative to the fits was always less than 1.5%. The CCTs (T_c) are shown in Table 1 for both *test* and *surround* lighting. In Figure 2 the spectral radiance distributions (in arbitrary units) for the lamps lighting the *test* to 200 cd/m^2 and 10 cd/m^2 are shown, obtained by reducing the current through the lamps (N) or by interposing neutral density filters (F) between the lamps and the target. As can be seen, neutral density filters alter the SPD much more as more filters are required to lower luminance. However, CCT is kept almost constant relative to the starting condition (4.2 A without

Table 1 Correlated colour temperature (K) of the lamps lighting the *test* and the *surround* at two luminance conditions (10 and 200 cd/m^2). These luminances are obtained by means of neutral density filters (F) or by reducing the current through the lamps (N)

	Method	T_c (K) at 10 cd/m^2	T_c (K) at 200 cd/m^2
Test	N	1940	2540
	F	2870	2850
Surround	N	1890	2380
	F	2780	2760

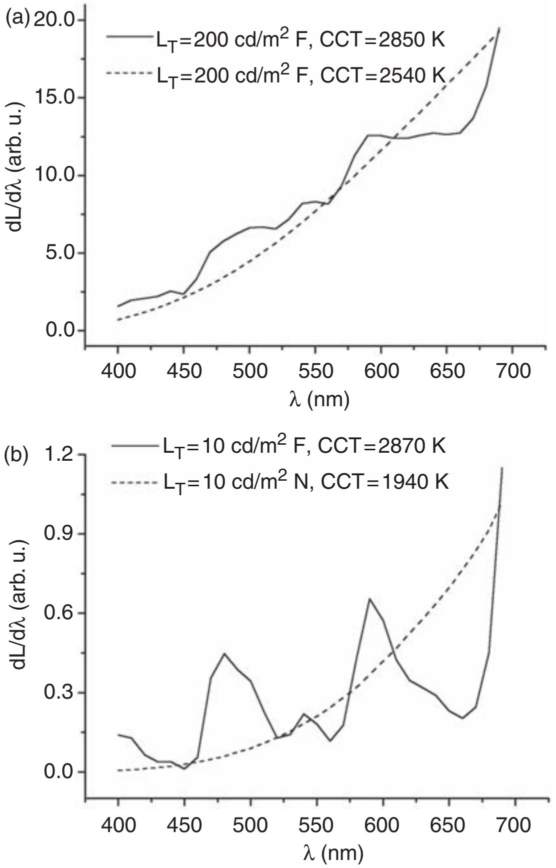

Figure 2 Spectral power distributions of the lamps lighting the *test* under the four illumination conditions considered, 200 cd/m^2 (a) and 10 cd/m^2 (b), both obtained by reducing the electrical current through the lamps (N) or by interposing neutral density filters (F)

filter and 2870 K). The SPDs for the lamps lighting the *surround* are very similar to those shown in Figure 2.

2.2 Observers

Twenty observers (25 eyes) were used, 15 were female and five were male, with ages ranging from 19 to 24 years old. The average and standard deviation of the ages were 21.2 ± 1.4 years old. The observers all signed an informed consent prior to any observation or measurement. After answering a questionnaire about their medical history, a complete optometric examination was performed including a long distance refraction as well as examination with a direct ophthalmoscope and a biomicroscope. Any potential observers with abnormal features revealed by the optometric examination were rejected. Similarly, those who were consumers of drugs or who had taken any kind of medicine during the days prior to the optometric examination or the measurements were rejected. Observers who were users of contact lenses were asked not to use them for at least two days before the optometric examination and the *CS* measurements. Refraction was performed to provide the maximum *visual acuity*.[20–24] All eyes with monocular *VA*-values worse than –0.08 log *MAR* (1.2 Decimal) with their best optical correction were rejected. The monocular visual acuities of our observers ranged from –0.08 to –0.28 log *MAR* (1.2 to 1.9 Decimal). All observers, even those who were emmetropic, used spectacles with their best refraction.

2.3 Test chart

A test chart based on the Pelli–Robson design was made.[25] It consisted of three sheets of paper, each with 16 triplets of letters (Figure 3). 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, which subtended 4.03 min arc at a distance of 5.2 m. Such small letter contrast sensitivity tests have been shown to be particularly sensitive to changes in lighting conditions as well as in ocular visual functionality.[14,15,26–28] Grey shades of letters were chosen so that the Weber contrast decreases in steps of 0.024 log units between consecutive triplets. This step is six times smaller than that found in most of the commercial CS targets. Further details of the design and fabrication of the optotypes and targets are noted by Aparicio et al.[14]

Figure 3 An example of the contrast sensitivity target

2.4 Procedure

Monocular contrast sensitivity measurements were made with a natural pupil so as to reproduce as much as possible the procedures used in clinical offices. Sixteen contrast sensitivity measurements were performed for each eye. They correspond to all combinations of the two *test* luminances ($L_T = 10$ and 200 cd/m^2) and the two *surround* luminances ($L_S = 10$ and 200 cd/m^2), obtained both by changing the current through the lamps or by inserting neutral density filters in front of them (Table 2). Observers were asked to read from the top of the chart and encouraged to guess the letters even when they were not clear.[25] 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

Table 2 Lighting conditions in which contrast sensitivity measurements have been made for all observers as well as the average obtained log(*CS*)-values and the associated 95% confidence intervals. *Test* and *surround* luminances are indicated. Symbol 'F' means that a neutral density filter was employed and symbol 'N' means that the luminance was achieved by changing the current through the lamps

Conditions	L_S (cd/m^2)	L_T (cd/m^2)	log(CS)	Confidence interval
1	200 (N)	200 (N)	0.935	0.057
2		200 (F)	0.924	0.049
3	200 (F)	200 (N)	0.933	0.056
4		200 (F)	0.935	0.054
5	10 (N)	200 (N)	0.843	0.072
6		200 (F)	0.844	0.072
7	10 (F)	200 (N)	0.833	0.071
8		200 (F)	0.846	0.072
9	10 (N)	10 (N)	0.614	0.073
10		10 (F)	0.583	0.077
11	10 (F)	10 (N)	0.608	0.080
12		10 (F)	0.566	0.073
13	200 (N)	10 (N)	0.548	0.073
14		10 (F)	0.530	0.078
15	200 (F)	10 (N)	0.556	0.069
16		10 (F)	0.556	0.073

correctly. Prior to each trial, 5 minutes were allowed for the observers to adapt to the illumination conditions.[29] The whole set of measurements for each observer lasted for 2.5 hours 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. It is important to note that, at 5.2 m between the observer and the test chart, head movements cannot significantly change the observer's performance. The order of measurements was randomised for different eyes.

3. Results

Average log contrast sensitivities and their associated 95% confidence intervals have been calculated for the sixteen lighting conditions tested (Figure 4 and Table 2). In Figure 4, vertical solid lines separate the two conditions with different L_S values. For each one of these L_S values, vertical dashed lines separate conditions where *surround* luminance is obtained by employing neutral density filters (F) or by reducing the output voltage of the variable transformer (N). Open symbols correspond to $L_T = 10\,\mathrm{cd/m^2}$ while solid ones correspond to $L_T = 200\,\mathrm{cd/m^2}$.

Figure 4 clearly shows that the lighting parameter which influences the contrast sensitivity most is the *test* luminance. This is a widely known result[4–9] and reflects the significant effect of foveal adaptation. As for the influence of *surround* luminances on log(CS) values, this seems to be different for the two L_T values. For $L_T = 10\,\mathrm{cd/m^2}$, a *surround* luminance of $10\,\mathrm{cd/m^2}$ produces higher log(CS) values than the *surround* luminance of $200\,\mathrm{cd/m^2}$. Conversely, for $L_T = 200\,\mathrm{cd/m^2}$, a *surround* luminance of $10\,\mathrm{cd/m^2}$ produces lower log(CS) values than the *surround* luminance of $200\,\mathrm{cd/m^2}$. The Student's *t*-test proves that there is a statistically significant difference ($p = 0.001$) between the log(CS) values for $L_T = 200\,\mathrm{cd/m^2}$, $L_S = 200\,\mathrm{cd/m^2}$ and those for $L_T = 200\,\mathrm{cd/m^2}$, $L_S = 10\,\mathrm{cd/m^2}$. This result confirms those obtained in previous work.[14] When comparing the log(CS) values for $L_T = 10\,\mathrm{cd/m^2}$, $L_S = 200\,\mathrm{cd/m^2}$ with those for $L_T = 10\,\mathrm{cd/m^2}$, $L_S = 10\,\mathrm{cd/m^2}$, the difference is also statistically significant ($p = 0.04$). This result will be discussed later. For these comparisons, all measurements

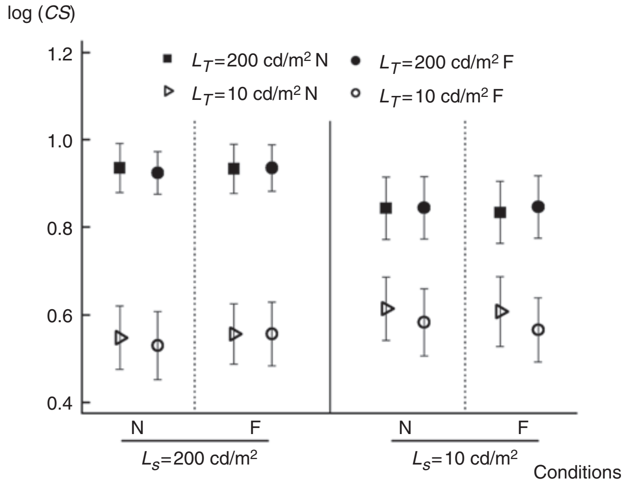

Figure 4 Average log(CS) and 95% confidence interval for each of the lighting conditions

performed at the same *test* and *surround* luminance conditions have been considered, independent of the SPDs of the light producing these luminances.

To specifically investigate the influence of the *test* lighting SPD on the log(*CS*) values, a graphical and a statistical analysis have been performed (Figure 5). For each data point of Figure 5, coordinate *x* represents the average log(*CS*) value obtained for a certain *test* and *surround* luminance condition with the *test* luminance obtained by employing neutral density filters (T = F). Coordinate y represents the log(*CS*) value obtained for the same *test* and *surround* luminance condition but, in this case, by reducing the current through the lamps lighting the *test* (T = N). Open triangles correspond to conditions in which filter is employed in the *surround* lighting (S = F) and solid squares correspond to conditions in which *surround* luminance is achieved by reducing the output voltage in the variable transformer (S = N). Horizontal and vertical error bars indicate the 95% confidence intervals.

All points in Figure 5 are so close to the unity-slope line that their error bars cross it horizontally and vertically. This is particularly clear for high log(*CS*) values, those obtained at $L_T = 200\,\mathrm{cd/m^2}$, but may require further analysis for measurements performed for lighting conditions corresponding to $L_T = 10\,\mathrm{cd/m^2}$. In these conditions, log(*CS*) seems to be slightly higher when *test* luminance is achieved by reducing the current through the lamps lighting the *test*, that is to say, for lower CCT according to Table 1.

In order to clarify this point, a further statistical analysis has been performed. In Figure 6 differences between coordinates '*y*' and '*x*' in Figure 5 have been calculated and represented as well as their error bars. The numbers on the horizontal axis represent the lighting conditions compared according to Table 2. After a statistical analysis performed with the Student's *t*-test and the Wilcoxon signed ranks test, it is concluded that no statistical significance ($p > 0.05$) is observed in the log(*CS*) values. A Bonferroni correction has been made in order to guarantee a global 95% confidence level. Therefore it is concluded that the different SPDs of the *test* lighting at the same luminance do not produce statistically significant changes in contrast sensitivity.

The influence of the SPD of the *surround* lighting on log(*CS*) values has also been

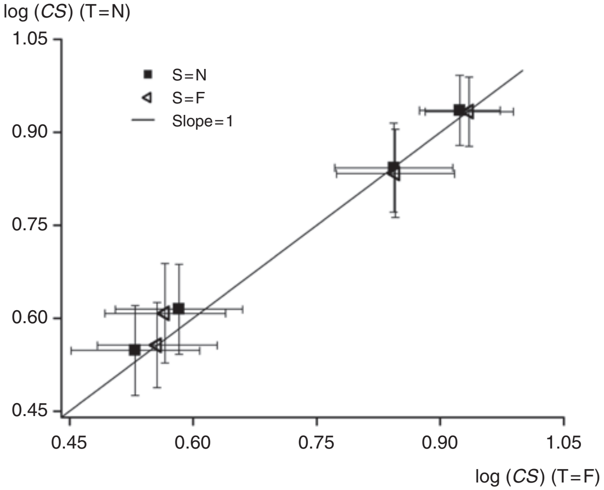

Figure 5 The influence of the spectral power distribution of the *test* lighting on log(*CS*)

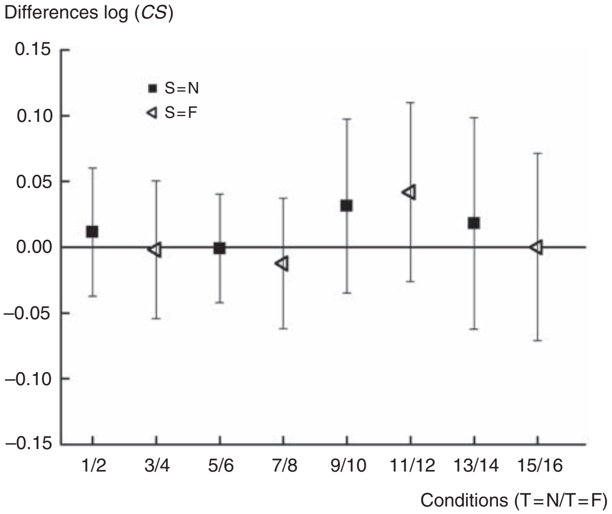

Figure 6 The differences between the 'y' and 'x' coordinates of Figure 5 for each *test* and *surround* lighting condition. They represent the effect of different methods of changing the spectral power distributions of the lamps lighting the *test*

analysed. In each point of Figure 7, coordinate x represents the average log(CS) value obtained for a certain *test* and *surround* luminance condition with *surround* luminance obtained by employing neutral density filters (S = F). Coordinate y represents the log(CS) value obtained for the same *test* and *surround* luminance condition but, in this case, by reducing the output voltage in the variable transformer connected to the lamps lighting the surround (S = N). Open triangles correspond to conditions in which filter is employed in the *test* lighting (T = F) and solid circles correspond to conditions in which *test* luminance is achieved by reducing the electrical intensity across the lamps (T = N). Horizontal and vertical error bars indicate the 95% confidence intervals have been depicted.

All points in Figure 7 are so close to the unity-slope line that their horizontal and vertical error bars cross this line. Once more this is clearer for the lighting conditions where *test* luminance is high and some doubt may appear for those conditions where $L_T = 10\,\mathrm{cd/m^2}$, that is, to say, for lower CCT in the surround according to Table 1.

In Figure 8, the differences between coordinates 'y' and 'x' in Figure 7 have been calculated and represented as well as their error bars. The numbers along the horizontal axis represent the lighting conditions compared according to Table 2. Once more, the Student's t-test and the Wilcoxon signed ranks test have been used and the Bonferroni correction has been made in order to guarantee a global 95% confidence level. It is concluded that no statistically significant differences are observed in the log(CS) values when changing the SPD by introducing neutral density filters or by reducing the output voltage of the variable transformer connected to the lamps lighting the surround.

As a final remark and, in order to assess a possible overestimation in the statistical significance of the data[30,31] due to considering two eyes for five of the subjects, we have repeated all the calculations by considering only one eye per individual, that is to say, with

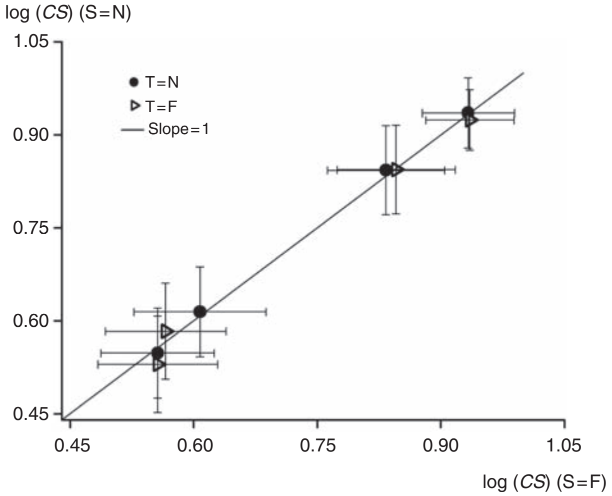

Figure 7 The influence of the spectral power distribution of the *surround* lighting on log(*CS*)

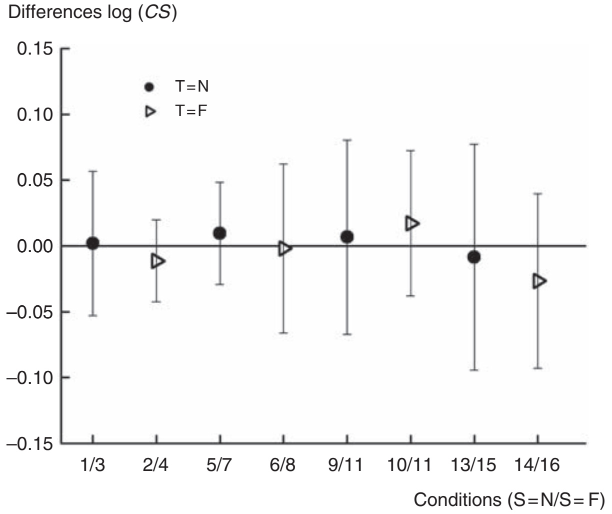

Figure 8 The differences between the ‘y’ and ‘x’ coordinates of Figure 7 for each *test* and *surround* lighting condition. They represent the effect of different methods of changing the spectral power distributions of the lamps lighting the *surround*

20 eyes. The results confirmed again that there is no statistically significant influence of the SPD of the light illuminating the *test* or *surround* on contrast sensitivity measurements. Moreover, a further statistical analysis allows us to confirm that the results shown in this work for 25 eyes are valid by themselves, since the correlations between the data coming from the two eyes of an individual (for the five subjects involved) are not significantly different from the correlations between any couple of eyes in this set of 25 eyes.

4. Discussion

Although it is well known in the literature, the first point to note about Figure 4 is the significant variation produced in log(*CS*) values just by changing the *test* luminance. In our experiment, the *CS* of letters subtending 4 min arc changes from 0.55 to 0.94 log units as *test* luminance increases from 10 to 200 cd/m^2 for a *surround* luminance of 200 cd/m^2. The neural adaptation of the visual system is usually recognised as responsible for this variation. This variation is the reason why it is important to reduce as much as possible the range of *test* luminances allowed in future recommendations on procedures for contrast sensitivity measurements.

The second point to note about Figure 4 concerns the different influence of the *surround* luminance on the log contrast sensitivity for different *test* luminances. The observed trend to increase contrast sensitivity for $L_T = 200$ cd/m^2 when *surround* luminance increases from 10 to 200 cd/m^2 has been explained by the dominant effect of pupil miosis and the resultant increment in the ocular modulation transfer function.[14] However, for *test* luminances of 10 cd/m^2, the increment in *surround* luminance from 10 to 200 cd/m^2 produces a statistically significant decrease in contrast sensitivity, which might be explained from the dominance of disability glare over pupil miosis when *surround* luminances are greater than *test* luminances.[14] It is important to highlight the young and visually normal nature of the observers in this study. It is likely that disability glare will play a much more marked role in older people, who are more likely to require contrast sensitivity tests for clinical reasons. Although not so important for contrast sensitivity measurements as *test* luminance, the range of allowed *surround* luminances should also be specified in future recommendations or perhaps, a *test* luminance should be investigated in future experiments for which changes in pupil size and disability glare are better balanced. In these conditions variations on *surround* luminance should have a minimal influence on contrast sensitivity measurements.

The most relevant result of this work concerns the influence of the SPD of the lighting of the *test* and *surround* visual fields on contrast sensitivity. As clearly shown in Figures 5 and 6 for *test* lighting, and in Figures 7 and 8 for *surround* lighting, when luminance is kept constant in both fields, there are no statistically significant increments or decrements in log(*CS*) values produced by just changing the current passing through the lamps or by inserting neutral density filters in front of the lamps lighting the *test* or the *surround*, at least for CCT in the range of 1900–2900 K approximately (Table 1).

These results might be physiologically explained by considering the effect of chromatic adaptation which occurs in the visual system when non-monochromatic illuminants are employed. This chromatic adaptation, according to the von Kries's model,[32] and the subsequent constancy in the colour perception is the result of similar changes in spectral sensitivity for the three types of cones involved in colour detection when the SPD is changed. This effect is clearly more evident when changes in CCT are small as are those considered in this work.

Of course, our results cannot be extrapolated to situations where quasi-monochromatic illuminants are employed and one type of cone is dominating the detection or recognition visual task. Previous results in the bibliography do not allow us to make definitive conclusions in this case. Ramamurthy et al.[33] did not find significant differences in grating *CS* when *tests* were illuminated with red, green or blue LEDs at test luminances of 45 cd/m^2. Fotios and Cheal[18] found greater contrast sensitivities for Landolt rings when employing low-pressure sodium lamps than when employing high pressure sodium or metal halide lamps. They attributed this improved visual performance to the better quality of the retinal image produced by this light source due to lower chromatic aberrations and not to the luminance (always in the mesopic range) or the SPD. Capilla et al.[34] also obtained slightly greater contrast sensitivities with red illumination on grating *tests* than when they were lit with mostly green or blue illuminants. In all cases, *test* luminance was around10 cd/m^2. They attributed these small differences to the ocular axial chromatic aberration, since these effects apparently disappeared when this chromatic aberration was compensated in the participants of their study. We could say that our results confirm those obtained by Fotios and Cheal[18] in achromatic tasks illuminated by high pressure sodium or by metal halide lamps, light sources with CCT similar to ours. Chromatic ocular aberrations might explain the apparent agreement between the results of Capilla et al. and Fotios and Cheal with quasi-monochromatic light sources, both results obtained in or near the mesopic. The small range of CCT of the achromatic light sources employed by Fotios and Cheal,[18] a range included in our experiment, might explain the agreement between our results and theirs. Concerning measurements performed in the photopic range, our results agree with those obtained by Ramamurthy et al.[33] and by Boyce et al.,[16] but not with those obtained by Berman et al.,[17] although the range of considered colour temperatures was very similar in these last two experiments.

It is also important to remark that the validity of our results may be restricted to a young population. The ageing effect on the transmittance of ocular media and on the diffusion of light for different wavelengths, particularly in the blue region, might alter significantly the influence of SPD on contrast sensitivity.

There are at least three reasons why this work is particularly relevant to the measurement of contrast sensitivity in clinical practice. First, in the case of *test* luminance, most projectors employ tungsten halogen lamps but modern devices also allow variations in luminance or contrast which are achieved by changing the current through the lamp. This work guarantees that the changes in SPD associated with such adjustments do not affect in a significant way the obtained contrast sensitivity measurements. Second, some psychophysical experiments which analyse the influence of *surround* luminance on contrast sensitivity have been performed by changing the current through the lamps.[11,14] The results obtained in the present experiment confirm the validity of the conclusions obtained in these studies and supports this technique for future research work. Third, the CCT used in our experiment do not cover the range over which fluorescent lamps operate; however, the lighting obtained by dimming tungsten halogen lamps does have a correlated colour temperature similar to that of the low pressure sodium lamp. Therefore, another important conclusion to be drawn from these results is the need to check if the contrast sensitivity measured in a clinical office with a *test* lit with tungsten halogen lamps is a valid indicator of the functional vision of an individual performing the driving task on a road lit with low pressure sodium lamps at a similar luminance.

In conclusion, it is clear that the study of the influence of SPD on contrast sensitivity measurements in optometric and ophthalmic offices is not finished yet. In fact, in many clinical offices fluorescent luminaires are used for *surround* lighting and, in the future, new video systems using CRT-, LCD- or LED-based displays are likely to be involved in visual assessment. Further research is required to quantify the influence, if any, of these completely different SPDs.

Acknowledgements

The authors thank S. González for his collaboration in the experimental arrangement, and the Consejería de Educación y Cultura de Castilla y León for their financial support under contracts VA090A08 and VA005A11-2. JA Aparicio wants to express his personal acknowledgment to the Organización Nacional de Ciegos de España (ONCE) for help. L. Issolio thanks the support provided by the grants CIUNT 26/E410, ANPCyT PICT06 1920 and CONICET PIP 308.

References

1 National Academy of Science. National Research Council (NAS-NRC). Committee on Vision. Report of Working Group 39. Recommended standard procedures for the clinical measurement and specification of visual acuity. *Advances in Ophthalmology* 1983; 41: 103–148.

2 International Standards Organisation. *Ophthalmic Optics - Visual Acuity Testing - Standard Optotype and Its Presentation* ISO:8596:1996. Madrid: AENOR, 1996.

3 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.

4 Blackwell HR. Contrast threshold of the human eye. *Journal of the Optical Society of America* 1946; 36: 624–643.

5 de Valois RL, Morgan H, Snodderly DM. Psychophysical studies of the monkey vision III. Spatial luminance contrast sensitivity tests of macaque and human observers. *Vision Research* 1974; 14: 75–81.

6 Kelly DH. Visual contrast sensitivity. *Optica Acta* 1977; 24: 107–129.

7 Banks MS, Geisler WS, Bennett PJ. The physical limits of grating visibility. *Vision Research* 1987; 27: 1915–1924.

8 Sucs FE, Uvijls A. Contrast sensitivity in retinitis pigmentosa at different luminance levels. *Clinical Vision Sciences* 1992; 7: 147–151.

9 Puell MC, Palomo C, Sánchez-Ramos C, Villena C. Normal values for photopic and mesopic letter contrast sensitivity. *Journal of Refractive Surgery* 2004; 20: 484–488.

10 Blommaert FJJ, Timmers H. Letter recognition at low contrast levels: effects of letter size. *Perception* 1987; 16: 421–432.

11 Cox MJ, Norman JH, Norman P. The effect of surround luminance on measurements of contrast sensitivity. *Ophthalmic and Physiological Optics* 1999; 19: 401–414.

12 Khanani AM, Brown SM, Xu KT. Normal values for a clinical test of letter-recognition contrast thresholds. *Journal of Cataract and Refractive Surgery* 2004; 30: 2377–2382.

13 Vizmanos JG, de la Fuente I, Matesanz BM, Aparicio JA. Influence of surround illumination on pupil size and contrast sensitivity. *Ophthalmic and Physiological Optics* 2004; 24: 464–468.

14 Aparicio JA, Arranz I, Matesanz BM, Vizmanos JG, Padierna L, González VR, Mar S, Menéndez JA, Issolio L. Quantitative and functional influence of surround luminance on the letter contrast sensitivity function. *Ophthalmic and Physiological Optics* 2010; 30: 188–199.

15 Rabin J. Luminance effects on visual acuity and small letter contrast sensitivity. *Optometry and Vision Science* 1994; 71: 685–688.

16 Boyce PR, Akashi Y, Hunter CM, Bullough JD. The impact of spectral power distribution on the performance of an achromatic visual task. *Lighting Research and Technology* 2003; 35: 141–161.

17 Berman SM, Navvab M, Martin MJ, Sheedy J, Tithof W. A comparison of traditional and high colour temperature lighting on the near acuity of elementary school children. *Lighting Research and Technology* 2006; 38: 41–52.

18 Fotios SA, Cheal C. Lighting for subsidiary streets: investigation of lamps of different SPD. Part 1 – Visual Performance. *Lighting Research and Technology* 2007; 39: 215–232.

19 Commission Internationale de l'Eclairage. *Light as a True Visual Quantity: Principles of Measurement*. CIE, Publication 41, Paris: CIE, 1978.

20 Jansonius NM, Kooijman AC. The effect of defocus on edge contrast sensitivity. *Ophthalmic and Physiological Optics* 1997; 17: 128–132.

21 Atchison DA, Woods RL, Bradley A. Predicting the effects of optical defocus on human contrast sensitivity. *Journal of the*

Optical Society of America A-Optics Image Science and Vision 1998; 15: 2536–2544.

22 Strang NC, Atchison DA, Woods RL. Effects of defocus and pupil size on human contrast sensitivity. *Ophthalmic and Physiological Optics* 1999; 19: 415–426.

23 Woods RL, Strang NC, Atchison DA. Measuring contrast sensitivity with inappropriate optical correction. *Ophthalmic and Physiological Optics* 2000; 20: 442–451.

24 Radhakrishnan H, Pardhan S, Calver RI, O'Leary DJ. Effect of positive and negative defocus on contrast sensitivity in myopes and nonmyopes. *Vision Research* 2004; 44: 1869–1878.

25 Pelli DG, Robson JG, Wilkins AJ. The design of a new letter chart for measuring contrast sensitivity. *Clinical Vision Sciences* 1988; 2: 187–199.

26 Rabin J. Optical defocus: differential effects on size and contrast letter recognition thresholds. *Investigative Ophthalmology and Visual Science* 1994; 35: 646–648.

27 Rabin J, Wicks J. The small letter contrast test – sensitivity, reliability and application. *Investigative Ophthalmology and Visual Science* 1995; 36: S943–S943.

28 Rabin J, Wicks J. Measuring resolution in the contrast domain: The small letter contrast test. *Optometry and Vision Science* 1996; 73: 398–403.

29 Wyszecky G, Stiles WS. *Color Science*. New York: Willey, 1982.

30 Ray WA, O'Day DM. Statistical analysis of multi-eye data in ophthalmic research. *Investigative Ophthalmology and Vision Science* 1985; 26: 1186–1188.

31 Murdoch IE, Morris SS, Cousens SN. People and eyes: statistical approaches in ophthalmology. *British Journal of Ophthalmology* 1998; 82: 971–973.

32 von Kries J. Influence of adaptation on the effects produced by luminous stimuli. In: MacAdam DL. (ed)*Sources of Color Science*. Cambridge MA: The MIT Press, 1970, pp. 109–119.

33 Ramamurthy V, Naredran N, Freyssinier JP, Raghavan R, Boyce P. *Determining contrast sensitivity functions for monochromatic light emitted by high-brightness LEDs. Third International Conference on Solid State Lighting. Proceedings of the SPIE 5187*, San Diego, CA, USA, Aug (2003) 05–07: 2004: 294–300.

34 Capilla P, Felipe A, Pons AM, Artigas JM. Effect of color on contrast sensitivity with two different accommodative stimuli. *Optometry and Vision Sciences* 1993; 70: 24–29.