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Light Source Spectrum, Brightness Perception and Visual Performance in Pedestrian Environments: A Review

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Abstract

This review considers the impact of light source spectral power distribution (SPD) on brightness perception and visual performance in mesopic conditions, with emphasis on the comparison of metal halide (MH) and high pressure sodium (HPS) lamps. Models of mesopic vision predict that SPD is a significant variable in that at a HPS photopic luminance of 0.100 cd/m^2, MH need only produce about 0.070 – 0.075 cd/m^2 to be seen as equally bright. However, attempts to validate the predictions of these models in the field have met with mixed success. As for visual performance, experimentation has shown that there are effects of SPD in mesopic conditions, but the magnitude of these effects depends on the nature the task. Three alternative approaches are suggested for comparing light sources with different SPDs in mesopic conditions.

1. Introduction

This review addresses the question: Do light sources with different spectral power distributions (SPD) create different perceptions of brightness and allow different levels of visual performance for pedestrians, even when providing the same photopic luminance? The answer to this question has important practical implications. Current lighting practice in pedestrian areas in the UK is to use high pressure sodium (HPS) light sources. In the USA and in some parts of Europe there is a trend to use metal halide (MH) or even compact fluorescent (CFL) instead of HPS light sources for pedestrian areas. HPS light sources have a higher photopic luminous efficacy and a longer life than either of these alternatives but these economic advantages would be offset if MH or CFL light sources could be used at lower photopic luminances yet still produce the same perception of brightness and levels of visual performance.

This review has three objectives. The first is to consider the evidence that SPD is an important factor in determining brightness and visual performance in the conditions experienced by pedestrians. The second is to determine whether the magnitude of the effects of SPD on brightness and visual performance, when applied to real light sources and the conditions experienced by pedestrians, is sufficient to get excited about. Assuming that it is, the third objective is to consider whether the effects of SPD have been validated, or if not, what sort of experimental work would be required to make such a validation.

2. Some physiology

Before considering the experimental evidence for an effect of SPD on brightness perception and visual performance, it is necessary to consider why photopic luminance alone might not be enough. This question is addressed to achromatic scenes. Where coloured surfaces are present, SPD obviously has an influence because it impacts both the photopic luminances and the colours of the surfaces, depending on the match between the SPD and the spectral reflectances of the surfaces. For an achromatic scene, the only variable is photopic luminance. Photopic luminance is calculated by multiplying the power in each wavelength of the SPD by the CIE Standard Photopic Observer (V_λ)[1].

There are three physiological reasons why photopic luminance based on the CIE Standard Photopic Observer may not be an accurate predictor of brightness for pedestrians

1. The CIE Standard Photopic Observer assumes a 2 degree field of view and a response dominated by the long- and medium-wavelength sensitive cone photoreceptors of the retina operating in the fovea[2]. For the pedestrian the visual field is much more extensive, so brightness will include a greater contribution from the short-wavelength sensitive cones[3]. This is true in both photopic and mesopic conditions.

2. The visual system is organized in three channels, one luminance channel where signals from the long- and medium-wavelength sensitive cone types are combined, and two colour channels where the differences between signals from different combinations of cone types are taken[4]. The CIE Standard Photopic Observer is based on data collected using either flicker photometry or step-by-step brightness matching, techniques that tend to minimize activity in the colour channels. Brightness perception is dependent on activity in all three channels. All three channels are active in both the photopic and mesopic states.

3. In the photopic state the cone photoreceptors are dominant. In the mesopic state, the rod photoreceptors become increasingly dominant over the cone photoreceptors as the light level is reduced. All active photoreceptors contribute to brightness[5].

As the long-, medium-, and short-wavelength cone photoreceptors and the rod photoreceptors all have different spectral sensitivities[6], light sources with different SPDs should produce different perceptions of brightness in the photopic and mesopic states even when the light sources produce the same photopic luminance.

As for visual performance, there is a crude division of responsibilities between the cone and rod photoreceptors. Cone photoreceptors are primarily devoted to colour perception and resolving fine detail, on-axis. Rod photoreceptors are more sensitive than cones which helps sustain some visual capabilities off-axis but rods provide no colour vision, and poor resolution [7]. This suggests that as the rod photoreceptors become dominant as light level is reduced through the mesopic range, the visual performance of tasks will deteriorate, the rate of deterioration depending on the relative extent to which the light source stimulates the rod and cone photoreceptors, and the visual requirements of the task. Where performance of the task is dependent on resolution of detail and perception of colours, the rate of deterioration will be rapid. Where no resolution of detail or colour is required, but only detection of the presence or movement of large objects off-axis, the rate of deterioration will be slow.

3. Exterior lighting for pedestrians

To know if the above physiology matters, it is necessary to consider the operating state of the pedestrian's visual system. Average horizontal photopic illuminances recommended in the UK for lighting pedestrian areas were in the range 3.5 to 10 lx[8] but in 2003 this was revised; BS EN 13201[9] describes the minimum maintained average horizontal photopic illuminance for six lighting classes, ranging from 2.0 lx to 15.0 lx. BS5489[10] identifies which of these lighting classes should be used according to the crime rate. It also permits a reduction of one class (i.e. a lower photopic illuminance) if lamps of high CIE General Colour Rendering Index are used ($Ra \geq 60$) such as metal halide. In the US the photopic illuminances recommended for pedestrian areas are in the range 2 to 10 lx [6]. Given a surface reflectance of 0.07, typical of asphalt and grass, these values imply photopic luminances in the range 0.04 to 0.33 cd/m^2, which means the pedestrian's visual system will usually be operating in the mesopic state. Of course, these are average photopic illuminances, so there will be higher photopic illuminances present in some parts of the lit area, and lower photopic illuminances in others. Given a reflectance of 0.07 and the conventional photopic luminance boundaries of the mesopic state[11] at about 0.001 cd/m^2 and 3 cd/m^2, the photopic illuminances needed to take the visual system outside the mesopic state are 135 lx for the photopic state and 0.045 lx for the scotopic. This implies that the lighting would have to be very non-uniform or be at very different average photopic illuminances than those recommended for the pedestrian's visual system to be operating outside the mesopic state.

Another aspect of the pedestrian environment that needs attention is the size of the visual field. Pedestrians make use of the full visual field, not just the fovea. This means that, with the visual system operating in the mesopic state, all types of cone photoreceptors and the rod photoreceptors will be active. Thus, there is every reason to believe that photopic luminance alone is not enough to predict brightness perception and visual performance for pedestrians, and that the light source SPD will have a significant influence.

4. What is important to pedestrians

While there is some reason for believing that SPD will have an impact on the perception of brightness and the visual performance of pedestrians, it is also worth considering why such impacts might matter to a pedestrian. Brightness is likely to matter because it is a fundamental visual perception that experience tells us is related to the amount of light present, and that in turn is related to how well we can see where we are going and what is happening around us. In other words, an area that is brightly lit after dark is perceived to provide good visibility and that, in the public mind, is likely to be more interesting and safer[12]. Pedestrians, particularly women, are advised to avoid poorly lit areas at night, and for poorly lit, read dark. Further, there is copious evidence that increasing the light level in an area from a low level will reduce the fear of crime, even if its effect on actual crime is dependent on other factors[7,13]. Light sources that provide a perception of greater brightness than others at the same photopic luminance are likely to be perceived as producing a safer environment.

As for visual performance, many different factors are likely to matter because the pedestrian is faced with many different tasks, ranging from the essential, such as recognizing the key features of the environment and detecting the raised edge of a paving slab, to the highly desirable, such as first detecting someone approaching and then seeing the details of the face of whoever is approaching[6, 14] Most such tasks first require off-axis detection followed by the use of the fovea to see detail, which can be characterized by measures of visual acuity and contrast sensitivity, and the ability to discriminate colours, which can be characterized by such measures as the accuracy of colour naming. Light sources that produce better off-axis detection, finer visual acuity, greater contrast sensitivity and more accurate colour naming than others at the same photopic luminance are likely to be considered as providing better lighting for pedestrians.

One other aspect of visual performance that deserves consideration is reaction time. It might be thought that small changes in reaction time are of little relevance for pedestrians, given the speed at which they are moving. However, many pedestrian fatalities are due to being struck by a motor vehicle[15] so the reaction time of drivers is also of interest to pedestrians. Light sources that produce shorter reaction times than others at the same photopic luminance can be considered to be making a contribution to the safety of pedestrians.

5. Models of mesopic vision

There have been many attempts to develop models of mesopic vision that can be used to predict the effects of light sources with different SPDs in mesopic conditions. These models vary in their complexity, the data on which they are based, and the generality of their application.

A large class of such models has been based on brightness matching [16-22]. These models all attempt to provide luminous efficiency functions for mesopic vision that transition between the CIE Standard Photopic Observer and the CIE Standard Scotopic Observer as light level is reduced. Such functions can be applied to the SPD of the light source to give the mesopic luminance provided by light source. If these models are correct, targets with equal mesopic luminance will look equally bright. Table 1 shows the ratio of photopic luminances for clear 400W MH and HPS light sources predicted by each model to provide equal brightness, the photopic luminance of the HPS being fixed at 0.1 cd/m^2. As can be seen, all but one model predict that a lower photopic luminance is required with the MH lighting than the HPS lighting for equal brightness.

Yet another model has been based on simple reaction time to the onset of an off-axis target[23]. This also results in luminous efficiency functions for mesopic vision that transition between the CIE Standard Photopic Observer and the CIE Standard Scotopic Observer. Again, each luminous efficiency function can be applied to the SPD of a light source to give the mesopic luminance provided by the light source. If this model is correct, light sources producing the same mesopic luminance will have the same reaction time to onset. This model[23] predicts, that with the photopic luminance of HPS set at 0.1 cd/m^2, the MH /HPS photopic luminance ratio for equal reaction time is 0.52.

Many of these models[16-23] are mathematically complex, so there have been attempts to provide a cruder bur simpler model. One such approach is based on the observation that both differences in brightness perception and reaction time to the onset of off-axis targets show very similar relationships for different photopic luminances and light spectra in the mesopic range[24]. Berman[25] suggests a simple closed-form equation that can be used to compare two different light sources for equal visual effect. Using this model, with the photopic luminance of the clear 400W HPS set at 0.1 cd/m^2, the MH/HPS photopic luminance ratio for equal visual effect is 0.58.

An even greater simplification has been the use of single-number multipliers. These multipliers can be applied to specific pairs of light sources to match their visual effect. For example, Table 2 shows lumen effectiveness multipliers developed by Lewin[26] based on the models of Adrian[22] for equal brightness and He et al[23] for equal reaction time. The lumen effectiveness multiplier is applied to the photopic lumens produced by the light source to give the number of effective lumens. For an HPS photopic luminance of 0.1 cd/m^2, these multipliers imply a MH/HPS photopic luminance ratio of 0.55 and 0.53 for equal brightness and equal reaction time respectively.

Another approach to a simple method for equating light sources with different SPDs in mesopic conditions is taken by Rea et al[27], based on the mesopic spectral sensitivity curves of He et al[23]. In this approach, light sources are equated on the basis of equal stimuli to the visual system rather than some equal response, i.e., providing the same photopic lumens and the same scotopic lumens. At a photopic luminance of 0.1 cd/m^2, this approach predicts that a clear 400W MH light source will require only 0.53 of the lumen output of a clear 400W HPS lamp to produce the same stimulation of the photoreceptors.

A more direct approach to obtaining single number multipliers has been undertaken by Lewis[28]. Using reaction times measured for a “realistic” task requiring the subject to judge which way a pedestrian at the edge of the road is facing, Lewis developed a series of multipliers. These multipliers indicate that at a photopic luminance of 0.10 cd/m^2 produced by a metal halide light source, a high pressure sodium light source would need to produce 0.78 cd/m^2 to achieve an equal reaction time, implying a MH/HPS photopic luminance ratio of 0.13. This is a much bigger effect than predicted by the models discussed above and provides a warning about a limitation of this approach, namely that the multipliers obtained will be specific for the task[26]. Depending on the task chosen, the magnitude of the multipliers can vary widely[27]. This is most evident in a study by Lingard and Rea[29] who examined the percentage detection of and reaction time to the onset of low and high contrast targets at different degrees of eccentricity under different light spectra in mesopic conditions. Both percent detection and reaction times showed differences between MH and HPS lighting, the differences varying with the photopic luminance, the luminance contrast of the target, and its eccentricity.

In addition to the differences between these models[16-23,26-28], it is important to appreciate that none of them predict any effect of SPD in photopic conditions, yet it is well established that SPD does influence brightness perception in photopic conditions[30-34]. Indeed, there are empirical models for predicting brightness under different light sources in photopic conditions based on this effect[32,34-37]. This does not mean that the mesopic models are incorrect. Rather it implies that as far as brightness is concerned they are incomplete, probably because they do not take activity in the colour channels of the visual system into account.

As for visual performance, it is claimed that the mesopic model of Adrian[22] can predict the effects of SPD on visual acuity, contrast sensitivity, and reaction time in mesopic conditions. Whether this is the best model of mesopic vision or whether many of the models produce similar predictions has yet to be determined[24]. What is clear is that the existence of these models and the data on which they are based demonstrates that, when vision is in the mesopic state, SPD does influence brightness perception and visual performance even when the light sources are producing the same photopic luminance. Further, at a photopic luminance in the middle of the range recommended for pedestrian facilities (0.1 cd/m^2), some of the models and multipliers suggest that MH lighting could provide the same brightness and the same reaction time at a photopic luminance low enough to offset the higher luminous efficacy of the HPS lamp. What is of interest now is the extent to which these predicted effects on brightness and visual performance have been demonstrated, for real light sources, in conditions representative of those experienced by pedestrians. This is necessary because the conditions experienced by pedestrians in the field can have wide differences in photopic luminance, and the light spectrum received at the eye can differ from that emitted by the light source because of the varying spectral reflectances present in the environment.

6. Evidence for real light sources in realistic conditions

6.1 Brightness

There is limited reliable evidence concerning the effect of real lamps on brightness perception in realistic mesopic conditions, despite the fact that the subject has been studied in both the laboratory and the field.

In the laboratory, Rea[38] had subjects view a coloured diorama of a landscape lit by either MH or HPS lamps. By moving a mirror it was possible to switch quickly between the two light sources. The photopic luminance of the background of the diorama provided by the MH was set at 0.01, 0.10 and 1.00 cd/m^2. At each photopic luminance, sixteen subjects were asked to adjust the amount of light from the HPS source until the diorama looked equally bright when alternately lit by the two light sources. The mean photopic luminance ratios for equal brightness (MH/HPS) were 0.71, 0.71 and 0.48 at 1.00, 0.10, 0.01 cd/m^2, respectively.

The conclusions from other laboratory studies of brightness perception using real lamps at low light levels are rejected from this review because of either small visual fields, insufficient data, or potential bias in procedures[39-45].

As for field studies of the effects of SPD on brightness in mesopic conditions, many have involved a direct comparison between real light sources fitted to real luminaires. While such tests are useful for guiding lighting practice, many are of little value for quantifying the impact of SPD alone. This is because of the uncertainty about the influence of differences in light distribution from the luminaires, and the glare from the luminaires due to different light source sizes, different reflectors, different ambient backgrounds, and so on.

One study that avoided these problems is that of Ferguson & Stevens[40] who compared mercury vapour (MV) and low pressure sodium (LPS) lamps fitted into the lanterns of a residential street. Each end of the street used different lamps so observers standing half way along the street could see both environments separately. A balanced order of presentation was used to counter other environmental differences. All the lanterns had substantially the same luminance distribution and physical dimensions. The LPS photopic luminance was held constant and the MV lamps dimmed, by varying the supply voltage, to give photopic luminance ratios (MV/LPS) of approximately 0.60, 0.75, 1.00 and 1.25. At each photopic luminance ratio observers gave their comparison of the two differently illuminated ends of the street using a five-point rating scale. The interpolated photopic luminance ratio (MV/LPS) for equal brightness was 0.6 when the observer's attention was focused on the lanterns. However, the interpolated photopic luminance ratio for equal brightness was 1.0 when the observers were asked to rate the brightness of the road surface. There are a number of possible reasons for this difference in photopic luminance ratios. One possibility is that the low reflectance ($r \approx 0.07$) of the road surface could lead to such low photopic luminances that the visual system would approach the scotopic state. Another, suggested by Rea et al.[46], is that subjective judgements can be based on various perceptual criteria, depending on how the subject interprets the instructions. It may be that, in this case, the observers were judging visibility of objects on the road rather than brightness of the road surface. Visibility is usually judged looking directly at objects, i.e., in foveal vision, despite the fact that off-axis visual performance is also important.

Boyce & Bruno[47] examined the perceptions of clear 250W and 400W HPS and clear 250W MH lighting in an open car park, the lamps being fitted in identical luminaires, mounted at identical heights. HPS lighting received the higher brightness ratings; however the lamps were not of equal photopic illuminance. Due to its higher luminous efficacy the HPS lighting produced a higher average photopic luminance than the MH lighting, even when the wattage was the same. Figure 1 shows the mean brightness ratings plotted against the average car park surface photopic illuminance, as seen by the subject, wearing and not wearing neutral glasses with a transmittance of 0.10. When wearing the glasses, the effective photopic illuminance is reduced to a tenth of the value it has when the subject is not wearing the glasses. As expected, there is a clear increase in brightness ratings with increasing photopic illuminance. Examination of Figure 1 also suggests that there may be small differences between the brightness of the car park when MH and HPS light sources are used, although what these differences are depends on whether or not the subjects were wearing the low transmittance glasses. When the subjects viewed the car park with the naked eye, extrapolating the brightness ratings for the HPS lamps suggests that at the same photopic illuminance, HPS lamps will produce a greater brightness than the MH lamps. However, when the subjects were wearing the glasses, extrapolating the brightness ratings for the HPS lamps indicates that, at the same photopic illuminance, the MH lamp will give a slightly greater perception of brightness. However, there is no statistically significant interaction between the light sources and whether the subjects were wearing the glasses or not, indicating that the SPD effects described above are due to chance.

[Figure 1]

Other field studies of brightness perception do not yield useful data because of either inadequate data reporting or uncontrolled extraneous variables[48,49]. Given this paucity of data that directly quantifies the effect of real light sources on the perception of brightness in conditions representative of those experienced by pedestrians, it is worth trying to gauge the impact of SPD on brightness from studies using different methods. One such approach is based on epidemiology. De Boer[50] et al.[51] used 16 observers to rate the road surface brightness in 70 streets on a nine-point scale from bad to excellent. The light sources used were incandescent, fluorescent, MV, and LPS. The mean brightness ratings plotted against road surface photopic luminance are shown in Figure 2. There is a clear effect of photopic luminance in these data, with increasing photopic luminance leading to a perception of greater brightness, but no clear effect of light source. This may be due to the variability caused by the differences in light distribution and source brightness.

[**Figure 2**]

Another approach is to match different light sources to a constant glare criterion. De Boer[50] et al[51] compared glare from different lamps in a simulated street. Fifty observers were asked to adjust the ratio of photopic luminaire luminance to photopic road surface luminance to identify the threshold of "just admissible glare", the road surface apparently being maintained at 1 cd/m^2 On average, the photopic luminaire luminance of a LPS lamp was set to 1.3 times that of a luminaire fitted with a tubular fluorescent lamp and 1.45 times that of the luminaire fitted with a MV lamp. If this glare threshold is taken to be the point at which brightness is high enough to start to create discomfort glare, then the results suggest that the LPS lamp required a higher photopic luminance than either the tubular fluorescent or MV lamps for equal brightness.

Overall, these laboratory and field studies of brightness perception reveal a confusing picture. There is some evidence that different SPDs do produce different brightness perceptions at the same photopic luminances in mesopic conditions but there are also studies that have failed to reveal any consistent effects of SPD. What is clear is that there are very few studies that have directly compared HPS and MH lamps on the basis of SPD alone, and those that have, have sometimes failed to reveal dramatic differences in brightness perception at the same photopic luminance despite the predictions of the models of mesopic vision.

6.2 Visual performance

Similar to the brightness studies, visual performance data are available from laboratory studies and from field studies. Laboratory studies are useful for determining if an effect occurs. Field studies are useful for determining if the effect survives the transfer to real conditions.

6.2.1 Threshold Measures

One group of laboratory data comes from threshold measures, i.e., performance at the limits of vision. Such measures are used because they have the maximum sensitivity to the stimulus conditions. These data includes visual acuity, contrast sensitivity, colour naming, and reaction time.

6.2.1.1 Visual Acuity

Eloholma et al[52] measured visual acuity for low (0.14) and high (0.94) contrast Landolt rings, at photopic luminances from 0.19 cd/m^2 to 5.2 cd.m^2, when illuminated by a daylight fluorescent lamp and red, green, and blue filtered fluorescent lamps. Visual acuity improved equally with increasing photopic luminance for all the light sources. This implies that there is no effect of SPD on visual acuity in the mesopic state. This result is not unexpected for the fovea, which is the part of the retina used when it is necessary to see fine detail. In the fovea there are no rod photoreceptors and few short–wavelength sensitive photoreceptors. This means foveal visual acuity is determined by the activity of the medium and long-wavelength sensitive photoreceptors, the very photoreceptors that account for the CIE Standard Photopic Observer. Therefore, it is to be expected that foveal visual acuity should be determined only by photopic luminance and not by SPD, even in the mesopic state. It is important to note that this conclusion cannot be expected to hold in the periphery, where rod and short-wavelength sensitive photoreceptors will be active in the mesopic state.

Support for this conclusion is available in Boyce and Bruno[47]. They measured visual acuity with a Landolt ring task under HPS and MH lighting in a car park, the observers viewing the target wearing and not wearing spectrally neutral glasses with a transmittance of 0.1. Figure 3 shows the number of Landolt ring gaps whose orientation was correctly identified plotted against the photopic luminance of the Landolt ring chart background. As would be expected, with improving visual acuity, the number of rings whose orientation was correctly identified increases with increasing photopic luminance, when the subjects were wearing and not wearing the glasses. For both viewing conditions, the increase in the number of Landolt ring gap orientations correctly identified with increasing photopic luminance can be well-fitted with a straight line, suggesting that the different SPDs of the two light sources has little role to play in determining visual acuity in the conditions studied, which include the mesopic.

Figure 3

There are a few earlier studies that examine the effect of real lamps on visual acuity in mesopic conditions but they offer insufficient information to justify their conclusions[50,51,53]. It is concluded that there is little evidence that SPD can affect visual acuity in mesopic conditions.

6.2.2 Threshold luminance contrast

Threshold luminance contrast is expected to show an effect of SPD in mesopic conditions, provided the targets used extend beyond the fovea. Lewis[54] measured threshold luminance contrast of back illuminated transparencies of sinusoidal contrast gratings. The gratings varied in contrast in steps of approximately 0.1 percent and subtended a visual field of approximately 13^O wide and 10^O high. At average photopic luminances of 10.0 & 3.0 cd/m^2 there was no difference between lamps but as the average photopic luminance decreased into the mesopic (1.0 and 0.1 cd/m^2) the MH lamp has a significantly lower relative luminance contrast threshold than the HPS or LPS lamps (Figure 4).

Figure 4

Boyce & Bruno[47] assessed contrast threshold with a Pelli-Robson chart of letters of constant size but decreasing contrast. Figure 5 shows the results obtained with HPS and MH lamps illuminating the chart, and being viewed wearing and not wearing glasses of transmittance 0.1. As would be expected, the number of letters correctly read increases with increasing chart background photopic luminance but there is little indication of a difference between the lamp types. This lack of effect is probably due to the small subtended size of the letters (12 min arc) , the chart being viewed from a distance of 13.7 m.

Figure 5

These results suggest that threshold contrast is affected by SPD in mesopic conditions, provided the target is of sufficient size that it extends beyond the fovea. However, this conclusion is based on only one study[54] so some validating data are desirable.

6.2.3 Colour Naming

One aspect of visual performance that is certain to be influenced by SPD is the ability to name colours. Chen[55] examined people's ability to name colours under seven different light sources at background photopic luminances ranging from 0.01 cd/m^2 to 10 cd/m^2 in logarithmic steps. Two sets of ten colour chips were used as stimuli. One set had red or green primary hues, all with a Munsell Value of 5, while the other had yellow or blue primary hues, all with a Munsell Value of 8. For each chip, the colour was named by asking the subject to identify the primary hue and then the secondary hue, e.g., for a chip in the red / green set, the primary hue is either red or green and the secondary hue is either yellow or blue. Colour naming accuracy was calculated as percentage of chips for which both the primary and secondary hues were named as they were under a broad-band light source at photopic light levels. Figure 6 shows the percentage correct colour naming for both chip sets combined and for Incandescent, MH, CFL, HPS, and LPS light sources. The accuracy of colour naming increases with increasing photopic luminance, yet there are clear differences between the light sources. Specifically, the incandescent, MH, and CFL light sources are all similar in colour naming accuracy and give more accurate colour naming than HPS, except at 0.01 cd/m^2. In turn, HPS gives more accurate colour naming than LPS, which has a percentage colour naming accuracy close to chance.

Figure 6

Boyce & Bruno[47] also measured colour naming ability by asking observers to name nine Munsell matte colour plates, all the possible colours being given them in a list. The nine colours were the basic colours identified by Boynton and Olson[56]. Performance was measured as the percentage of correctly identified colours. Figure 7 shows the percentage of colours correctly identified, plotted against the photopic illuminance on the colour plates, for both MH and HPS lamps, and with the plates being viewed by observers with and without glasses of transmittance 0.1. Two points are clear from this figure. The first is that more accurate colour naming is possible under MH lighting than HPS, despite the lower photopic illuminance. Regression lines drawn through the data for each light source separately suggest that at photopic luminance of 0.1 cd/m^2 for HPS, the same percentage of colours correctly named is achieved with MH at a photopic luminance of 0.030 cd/m^2, i.e., at a MH/HPS photopic luminance ratio of 0.31. The second point is that over the photopic illuminance range used, increasing photopic illuminance increases the accuracy of colour naming for the same SPD.

Figure 7.

It can be concluded that MH lamps ensure more accurate naming of basic colours than HPS in the mesopic conditions, until the scotopic state is approached.

6.2.4 Reaction time

Lewis[54] compared reaction times under five lamps - incandescent, MV, HPS, LPS and MH, at photopic luminances of 0.1, 1.0, 3.0 and 10.0 cd/m^2. Sinusoidal contrast gratings subtending 13^O by 10^O were presented at high luminance contrast (five times above each subject's own threshold contrast) and the subject's task was to correctly identify the orientation (horizontal or vertical) of the grating as soon as possible after its onset. As expected, the higher photopic luminances yielded the shorter reaction times. At the photopic levels (3.0 and 10.0 cd/m^2) differences between the lamps are not significant; at the two mesopic levels (0.1 and 1.0 cd/m^2) differences in reaction time between lamps are statistically significant, the MH offering the shortest reaction time and the HPS and LPS offering the longest reaction times (Figure 8). The MH at 0.1 cd/m^2 yields approximately the same reaction time (577 ms) as the HPS at 1.0 cd/m^2 (568 ms). If the photopic luminance for HPS is set at 0.1 cd/m^2, Figure 8 implies that MH would require a lower photopic luminance for equal reaction time, but the available data do not allow an accurate prediction of what the photopic luminance might be.

[Figure 8]

Lewis[54] also compared reaction time using a more realistic task, one that included non-visual cognitive processing. The task comprised two transparencies which depicted a woman, in one facing the road and in the other facing away from the road. Subjects were required to correctly identify which way the woman was facing. These tests used the same four photopic luminances and five lamps as the grating task. Again it was found that there were statistically significant differences in reaction time under the different lamps at the two photopic luminances in the mesopic range (0.1 cd/m^2 and 1.0 cd/m^2) but that these differences were not significant at the two photopic luminances (3.0 cd/m^2 and 10.0 cd/m^2) (Figure 9). At 0.1 cd/m^2 HPS yields a reaction time of 1129ms and the trend for MH between 1.0 to 0.1 cd/m^2 suggests that for MH a lower photopic luminance would produce the same reaction time. However, the data available are insufficient to make an accurate prediction of what that lower photopic luminance might be.

[Figure 9.]

He *et al* [57] compared reaction times under HPS and MH lamps to the onset of an achromatic 2^O disc, presented either on-axis or 15^O off-axis at background photopic luminances between 0.003 and 10.0 cd/m^2. The results show that for both on-and off-axis presentations, reaction times decrease with higher photopic luminances. For off-axis targets there was no significant difference between the lamps at photopic luminances, but for photopic luminances below approximately 1.0 cd/m^2 the MH lamp produces a shorter reaction time than the HPS lamp: at 0.100 cd/m^2 the reaction time under HPS is matched by the MH lamp at a photopic luminance of 0.052 cd/m^2 i.e., at a MH/HPS photopic luminance ratio of 0.52. For on-axis targets there was no significant difference between the lamps at all photopic luminances. This difference between the results of He *et al*[57] and Lewis[54] can be explained by the size of the stimulus. He *et al* used a task the same size as the fovea whereas Lewis used a task much larger than the fovea.

It can be concluded that lamp spectrum does not affect reaction times in photopic conditions. In mesopic conditions, if the target stimulates only the fovea then lamp spectrum will not affect reaction times but if the target stimulates regions outside the fovea, which might be an on-axis task of size greater than 2^O or an off-axis task of any size, then lamp spectrum does affect reaction times.

6.2.5 Visual search

Walkey[58] describes an extensive series of studies of the effect of photopic luminance contrast, scotopic luminance contrast, and colour difference between the target and the background, on search time in mesopic conditions. Although different SPDs were not used in this study, the results imply that SPD is likely to be important for visual search. The basic finding was that in mesopic conditions the main determinant of search time was scotopic luminance contrast. This was particularly the case as conditions approach the scotopic state. As conditions approached the photopic state, the photopic luminance contrast and the colour difference became more important. These findings imply that in mesopic conditions, MH will ensure faster visual search than HPS at the same photopic luminance.

6.3 Performance of real tasks

All the above studies use real light sources and examine activities designed to determine the limits of performance of the visual system in mesopic conditions. There are also a small number of field tests undertaken with real light sources, but using activities representative of those undertaken by pedestrians.

Raynham & Saksvikrønning [59] compared facial recognition under HPS and CFL lamps - observers walked towards a person until that person’s face could be recognised. A second series of tests was intended to employ peripheral vision by having the observer walking towards two people spaced 3m apart and having the task of identifying both, but in the absence of a fixation point or restrained head positioning it is almost certain that the observer used head and eye movements to scan both people using foveal vision. The results show that faces can be recognised at a greater distance under CFL lighting than under HPS lighting, implying that for facial recognition at a given distance the CFL lamp requires a lower photopic illuminance than the HPS lamp. However, the absence of variance data prevents determination of statistical significance.

Eloholma *et al* [60] compared on-axis and off-axis (15^O) visibility under HPS and MH lamps. In a long underground tunnel, observers were required to indicate at what distance they could just detect a pedestrian walking towards them. It was found that SPD did not affect the task when performed with foveal or off-axis vision at either photopic luminance (0.1 and 1.5 cd/m^2). In a second test series using one trained observer they did find better performance under the MH lamps than the HPS lamps with off-axis (20^O) viewing at the lower road surface photopic luminance: the pedestrian could be identified at a lower photopic luminance under MH lamps (~0.0025 cd/m^2) than under HPS (~0.0035 cd/m^2) implying a MH/HPS photopic luminance ratio of 0.71.

Rea et al.[46] carried out a field experiment in which reaction times to a change of character of luminance contrast 0.75 on a changeable message sign, located 15 degrees off-axis, were measured. The setting was a roadway lit by two different types of MH lamps or HPS lamps, to give a road surface photopic luminance of 0.2 cd/m^2. A lower road surface photopic luminance was achieved by having the subject wear glasses of transmittance 0.1. Figure 10 shows the mean reaction times and Figure 11 shows the percentage of changes in message sign character that were missed, at the two road surface photopic luminances. It is clear from these figures that the MH lighting produces much shorter reaction times and many fewer misses for the detection of these off-axis changes, particularly at the lower road surface photopic luminance (0.02 cd/m^2)

[Figures 10 & 11]

Boyce & Bruno[47] measured the ability of observers to identify which of ten objects, some of which would be considered dangerous, e.g., a gun or a knife, a person 10.5 m away was carrying. This was done in a car park, lit by either MH or HPS lighting, and with the observer either wearing or not wearing glasses with a transmittance of 0.1. The percentage of objects correctly identified increased as the photopic illuminance on the parking lot increased, but there was no statistically significant difference between the light sources.

Overall, these studies of realistic tasks reveal a wide range of effects. Some studies show better performance under MH lighting relative to HPS lighting, but others show no difference. The problem with such studies is that the conclusions to be drawn from them depends nature of the tasks, specifically, the balance between on- and off-axis activity and how close the performance is to threshold. The questions to be addressed when considering these results are whether the task is meaningful for the application, and whether the absence of effects is due to a lack of sensitivity, or simply because there really is no effect.

7. Discussion

This review was undertaken with three objectives

- To determine whether or not SPD is an important factor in brightness perception and visual performance in the conditions experienced by pedestrians

- If SPD is an important factor, deciding whether the magnitudes of these effects of SPD are sufficient to justify the use of MH light sources as an alternative to HPS

- If the magnitude of the effects is sufficient, considering whether the effects of SPD have been validated, or if not, what sort of experimental work would be required to make such a validation.

For brightness perception, the various models of mesopic vision based on matching brightness all show that SPD is an important factor in mesopic conditions. As for the relative brightnesses of MH and HPS lamps, all the models of mesopic vision, with one exception, show that at a photopic luminance of 0.1 cd/m^2 for HPS, the MH lamp will produce the same perception of brightness at a lower photopic luminance. Specifically, based on the models[16-18,20-22,25,26], the mean MH/HPS photopic luminance ratio for this condition is 0.75 with a standard deviation of 0.19. If the unique prediction of the Trezona model[20] is eliminated, the mean MH/HPS photopic luminance ratio is reduced to 0.70 with a standard deviation of 0.14. This suggests that at a photopic luminance for HPS of 0.100 cd/m^2, MH lamps need only produce 0.070 - 0.075 cd/m^2 to produce an equal perception of brightness. Such a reduction is just about enough to offset the higher photopic luminous efficacy of HPS. Of course, this ignores the added advantage of MH lamps that they will make most colours appear more saturated than HPS lamps and more saturated colours in a scene will enhance the perception of brightness[61,62].

Three caveats should be attached to this conclusion. The first is that the magnitude of the effect changes with the photopic luminance. Specifically, the models of mesopic vision based on brightness perception all tend to a MH/HPS photopic luminance ratio of 1.0 as the photopic luminance is increased to 1.0 cd/m^2 and tend to a value of about 0.5 as the photopic luminance is decreased to 0.001 cd/m^2 The second is that there is some uncertainty in the MH/HPS photopic luminance ratio because there are several different forms of MH lamp, different manufacturers using different additives to the discharge resulting in a number of different SPDs for MH[63]. It is unclear from the descriptions of almost all of the studies what exact form of MH lamp was used. The third comes from the apparent difficulty experienced by those who have sought to demonstrate such brightness differences between MH and HPS in the field. This difficulty may have occurred for a number of reasons. One may have been that different people use different cues to judge brightness when viewing a real scene. Another may have been ambiguous instructions given to subjects. Yet another may have been inadequate control of variables other then SPD, such as light distribution, luminaire photopic luminance, light source size, and colour content of the scene, although if this is the reason it suggests that the effect of SPD on brightness is not sufficiently robust to overcome many of the other differences that may exist between real lighting installations. Whatever the reason, until the large differences in brightness predicted for MH over HPS by the models of mesopic vision can be reliably demonstrated in the field, some caution is required in attempting to apply these predictions.

Turning now to visual performance, the effect of SPD in conditions representative of those experienced by pedestrians is somewhat ambiguous. From the studies reviewed, it is clear that the effect of SPD on visual performance is dependent on the nature of the performance required. For a start, on-axis visual acuity in mesopic conditions is not affected by SPD. This implies that photopic luminance is a good metric for quantifying the impact of lighting on foveal tasks in mesopic conditions. This is as it should be because the fovea is dominated by long- and medium-wavelength sensitive cone photoreceptors with few short-wavelength cone and rod photoreceptors. Therefore, the spectral sensitivity of the fovea should correspond to the CIE Standard Photopic Observer throughout the photopic and mesopic range.

As for off-axis visual acuity and other basic visual functions outside the fovea, these are influenced by SPD in the mesopic. This occurs because outside the fovea, short-wavelength cone photoreceptors and rod photoreceptors are much more common and these photoreceptors are not involved in the determination of the CIE Standard Photopic Observer. This implies that for off-axis visual acuity and other basic visual functions that extend beyond the fovea, photopic luminance will not be an accurate predictor of visual capabilities in the mesopic state.

As for suprathreshold tasks, here the impact of SPD is even more variable. This is because such tasks can vary widely in their sensitivity to lighting conditions because they vary in the extent to which vision is important for doing the task, and, even when vision is important, different tasks have different visual requirements.

From the studies of visual performance examined, it is apparent that the range of MH/HPS photopic luminance ratios for equal performance in mesopic conditions is very large, the actual value for any specific task depending on the exact nature of the task. The reason for this wide variability, something that has also been noted by Rea et al[27], is that task performance depends on many factors other than the spectrum of the illuminant. This means it is impossible to draw a simple conclusion about SPD and visual performance in relation to pedestrians. Rather, the question needs to be reframed in terms of what aspects of visual performance are important for pedestrians. Until this question is answered, it is impossible to decide if SPD is important for visual performance in conditions representative of those experienced by pedestrians. What can be said from the available data is that MH either has no effect on visual performance or a positive effect in the sense of shorter reaction times, or more frequent off-axis detection etc. Thus, at equal photopic luminance, MH will provide either the same or better visual performance than HPS. However, this is not necessarily true if the MH lamp provides a lower photopic luminance than the HPS lamp because then the positive effect of SPD is set against the persistently negative effect of lower photopic luminances on visual performance in mesopic conditions. At what point this trade-off achieves balance will almost certainly depend on the exact nature of the task.

The above discussion implies the answer to the third objective. It is not possible to conclude that the effects of SPD on visual performance in conditions representative of those experienced by pedestrians have been validated when the effects are so dependent on the task. The effect of SPD on brightness perception is closer to being validated but, even then, many of the data are derived from abstract experiments involving uniform, self-luminous fields rather than real exterior scenes. Further, attempts to validate the predicted relative brightnesses in the field have met with mixed success. All this suggests three alternatives for assessing the relative merits of MH and HPS lamps for use in pedestrian areas. One is to make the comparison on the basis of brightness perception. If this approach is adopted, then what is needed is a convincing field test of the predictions of the models of mesopic vision. Another is to make the comparison on the basis of visual performance. If this approach is adopted, it is first necessary to conduct studies aimed at identifying what aspects of visual performance are most meaningful to pedestrians, followed by measurements of the performance of these meaningful tasks under MH and HPS lighting in conditions representative of pedestrian environments. Yet another is to make the comparison on the basis of equal stimuli to the rods and cones of the human visual system, as proposed by Rea et al[27] This approach uses visual stimulus rather than visual response as a basis for comparison but it is implicit that equal stimulation to rods and cones will ensure similar if not equal visual response. It would be worthwhile testing this assumption for meaningful activities.

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Table 1 Photopic luminance ratio (MH/HPS) for predicted equal brightness perception with the photopic luminance of HPS being set at 0.1 cd/m^2

Model	MH / HPS photopic luminance ratio
Palmer 1996[16]	0.77
Kokoschka and Bodmann, 1975[17]	0.79
Ikeda and Shimozono, 1981[18]	0.89
Trezona, 1991[20]	1.11
Sagawa and Takeichi 1992[21]	0.78
Adrian 1998[22]	0.55

Table 2: Lumen effectiveness multipliers for different light sources at a photopic luminance of 0.1 cd/m^2. HPS is the reference light source to which all the others are compared (after [26])

Light Source	Based on Adrian (1998)[22]	Based on He et al. (1998)[23]
High pressure sodium (HPS)	1.00	1.00
Metal halide (MH)	1.82	1.88
Mercury vapour (MV)	1.38	1.53
Low pressure sodium (LPS)	0.61	0.64

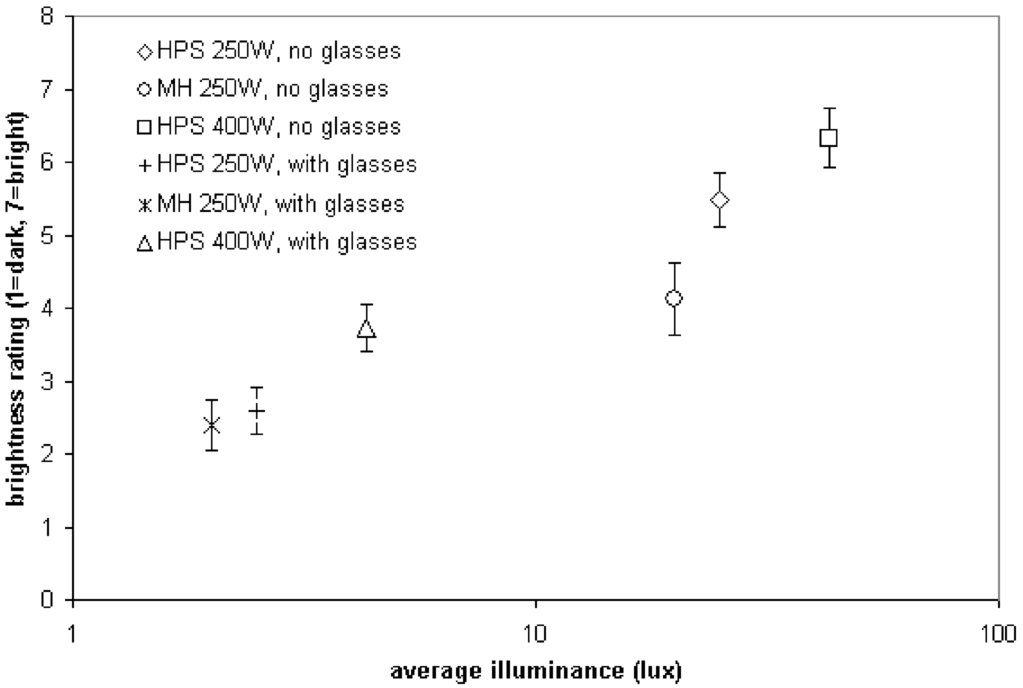

Figure 1 Mean brightness ratings for car park lighting plotted against average photopic illuminance. The car park was lit either by 250W HPS, 400W HPS or 250W MH lamps, and viewed by subjects wearing or not wearing glasses of transmittance 0.1 [after [47]].

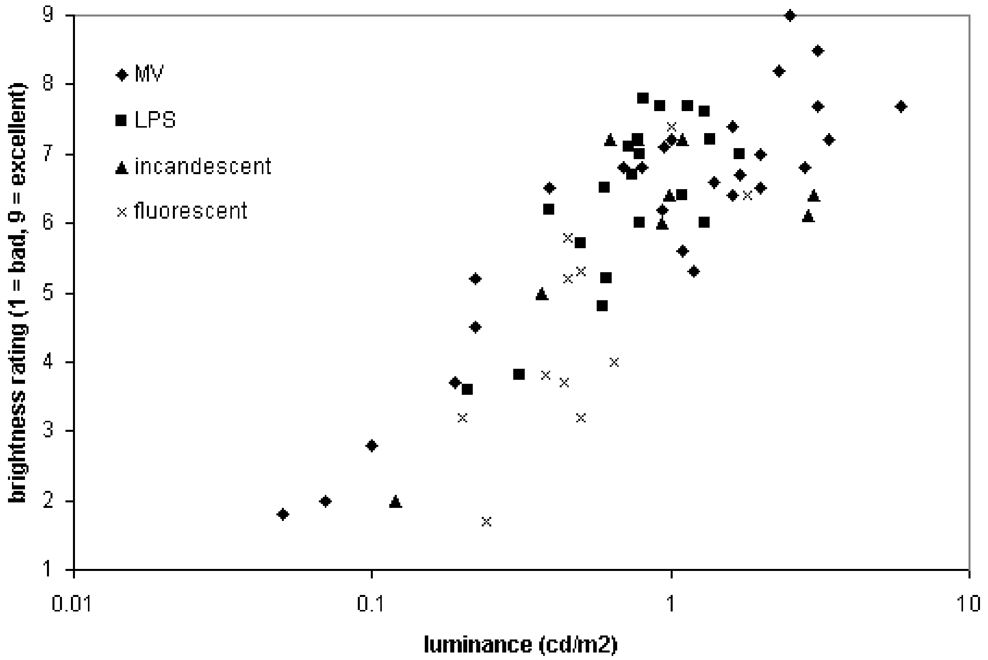

Figure 2 Mean brightness ratings of 70 road surfaces lit by MV, LPS, incandescent and fluorescent lamps, plotted against road surface luminance [after [50,51]].

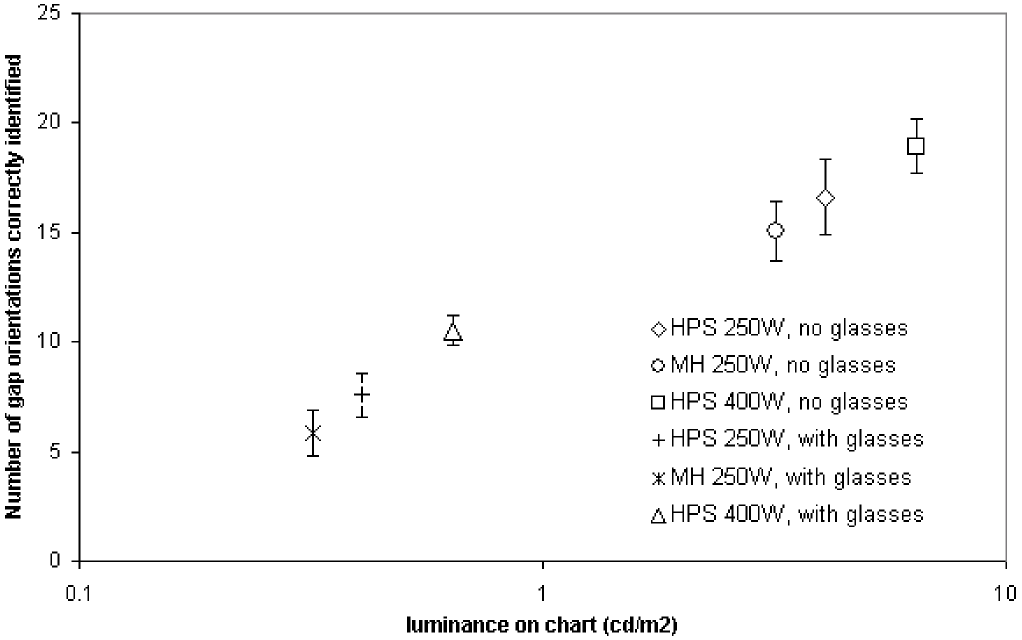

Figure 3 Mean number of Landolt ring gap orientations correctly identified plotted against photopic luminance of chart background. The chart was lit either by 250W HPS, 400W HPS or 250W MH lamps, and viewed by subjects wearing or not wearing glasses of transmittance 0.1, [after [47]].

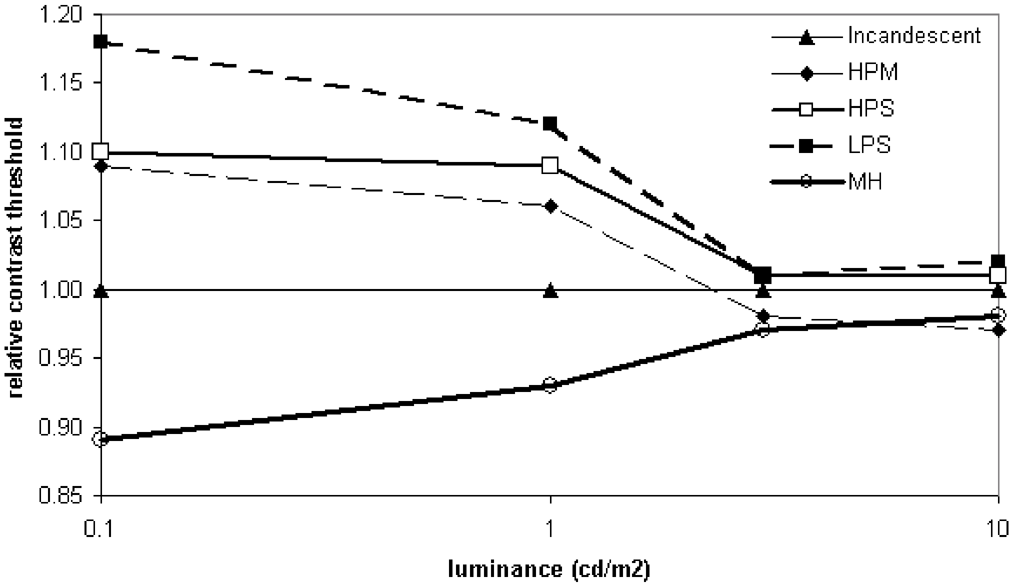

Figure 4 Mean relative luminance contrast threshold for a sinusoidal grating plotted against average photopic luminance of the grating. The luminance contrast thresholds for different light sources are expressed relative to that for the incandescent lamp, [after [54]]

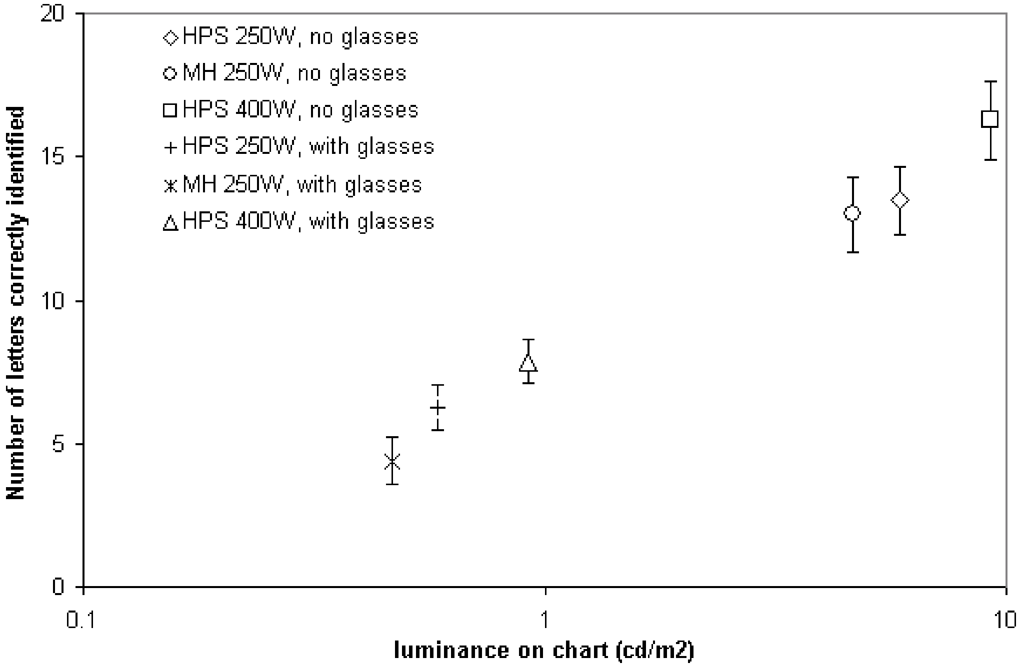

Figure 5 Mean number of letters correctly identified on the Pelli-Robson chart plotted against photopic luminance on the chart. The chart was lit either by 250W HPS, 400W HPS or 250W MH lamps, and viewed by subjects wearing or not wearing glasses of transmittance 0.1, [after [47]].

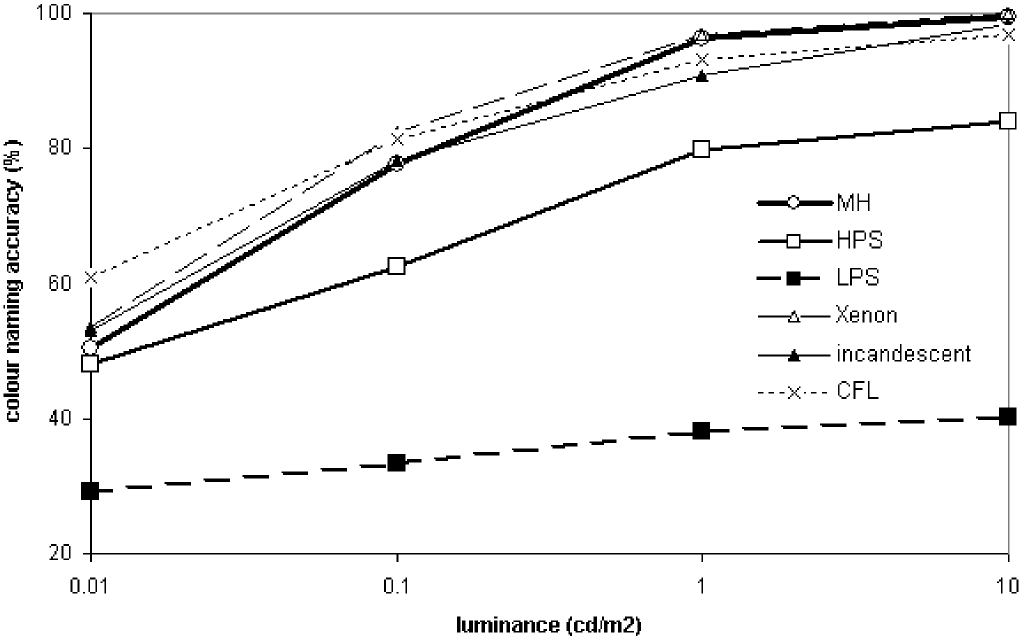

Figure 6 Percent colour naming accuracy for primary and secondary hues lit by different sources plotted against photopic luminance of the background against which the colours were displayed, [after [55]].

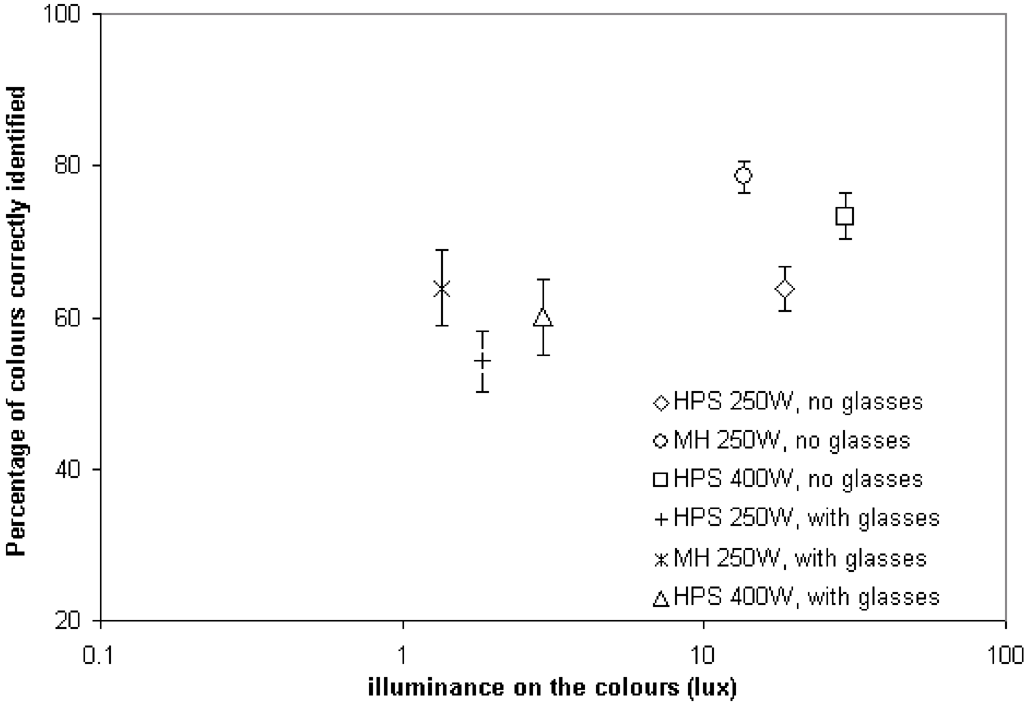

Figure 7 Percent of colours correctly identified plotted against the photopic illuminance on the colour plates. The colour plates were lit by either 250W HPS, 400W HPS or 250W MH lamps, and viewed by subjects wearing or not wearing glasses of transmittance 0.1, [after [47]]

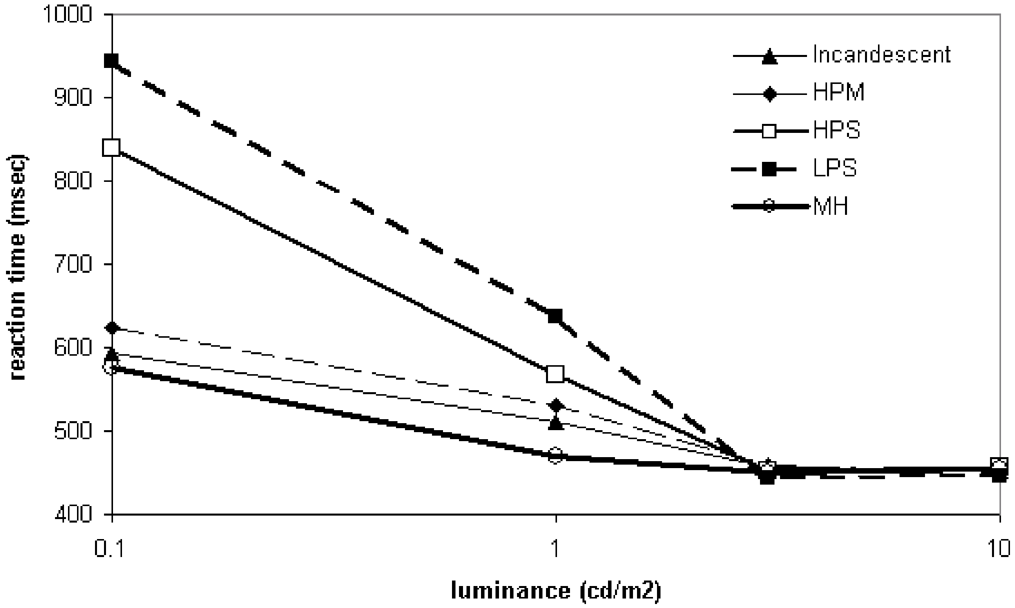

Figure 8 Mean reaction times to the on-set of a sinusoidal grating plotted against the average photopic luminance of the grating under various light sources, [after [54]]

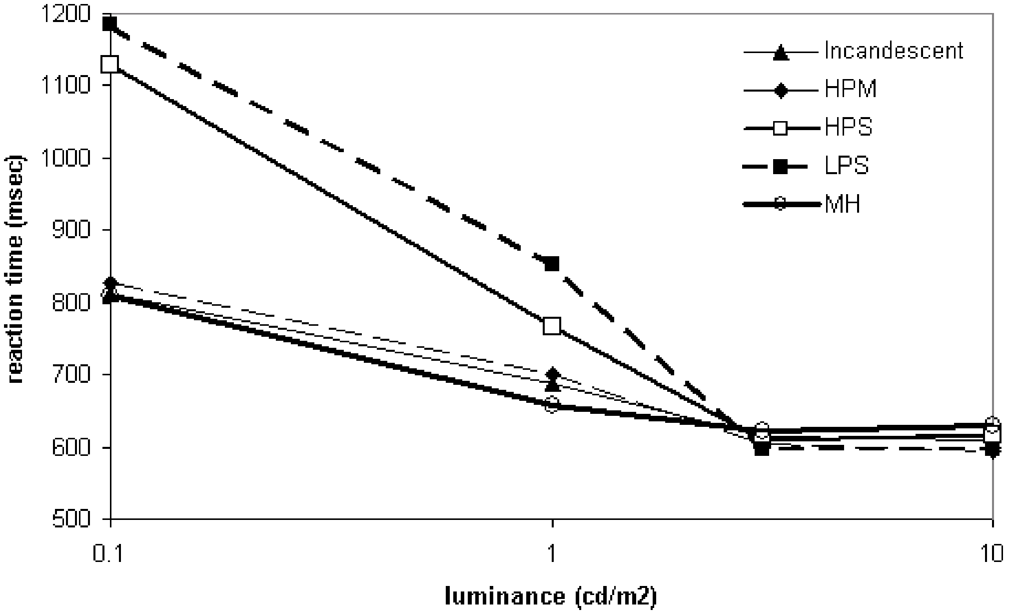

Figure 9 Mean reaction times for detecting which way a pedestrian is facing in a transparency plotted against the average photopic luminance of the transparency under various light sources, [after [54]]

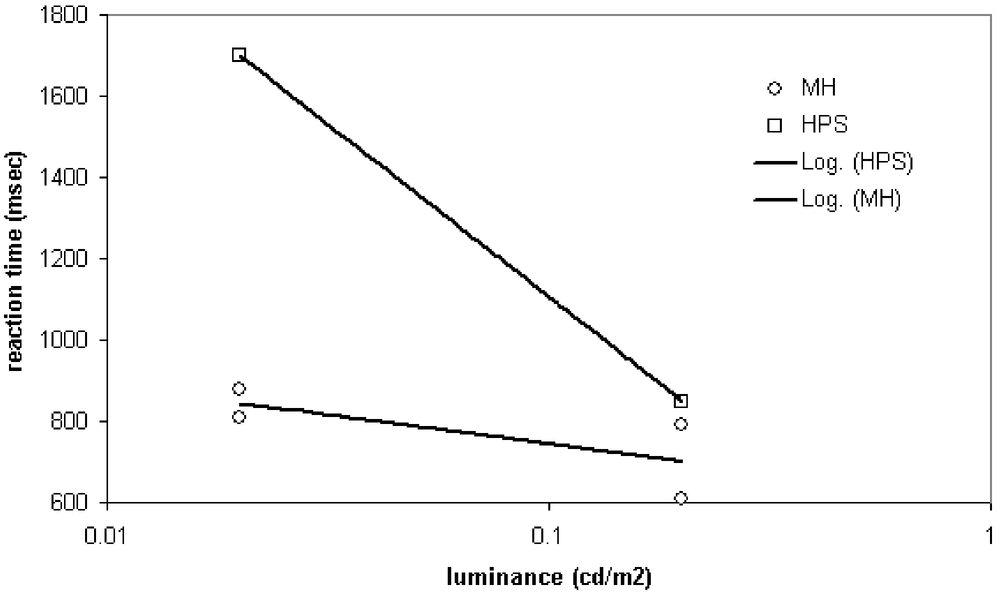

Figure 10 Mean reaction time to the change of a character in a message sign located 15 degrees off-axis, plotted against the photopic luminance of the road surface, [after [46]].

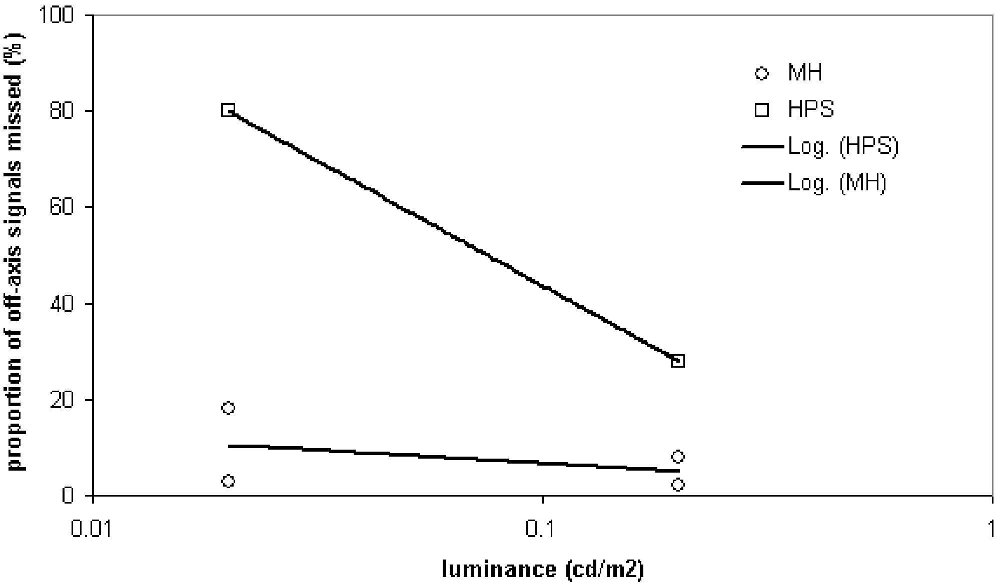

Figure 11 Percentage of off-axis signals missed plotted against the photopic luminance of the road surface, [after [46]].