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Lighting for Subsidiary Streets: Investigation of lamps of different SPD. Part 1 – Visual Performance

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Abstract

British Standard BS5489-1: 2003 permits a trade-off between colour rendering and illuminance for lighting in subsidiary streets – if lamps of high colour rendering index such as metal halide are used instead of high- or low-pressure sodium lamps, a lower average illuminance can be used. A series of tests were carried out under mesopic conditions to validate the trade-off and this article reports on the new visual performance results. Four tests were carried out: acuity of achromatic and chromatic targets, achromatic contrast detection threshold and colour identification, these being for on-axis targets. It was found that SPD did not affect the performance of achromatic tasks except for an increase in contrast detection threshold under LPS lamps. The performance of an acuity task using coloured targets displayed interaction between target colour and SPD. Colour naming accuracy was found to be significantly higher for metal halide lamps than for sodium lamps. For all tasks there was a reduction in visual performance at lower illuminances, and therefore a reduction in design illuminance leads to a reduction in the performance of some visual tasks which may not be offset by lamp SPD. Implications for the performance of real pedestrian tasks are discussed.

1. Introduction

In the UK, where lighting in subsidiary streets is designed for the demands of the pedestrian, the design illuminance is specified through two documents. BS EN 13201-2:2003[1] describes the minimum maintained average horizontal photopic illuminance for six lighting classes, the S-series, ranging from S6 = 2.0 lx to S1 = 15.0 lx, with intermediate levels being 3.0 lux, 5.0 lux, 7.5 lux and 10.0 lux. Given a surface reflectance of 0.07, typical of asphalt, these illuminances 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.

BS5489-1:2003[2] identifies the selection of a lighting class according to crime rate and traffic flow, and furthermore permits a reduction of one S-class (i.e. a reduced illuminance) if lamps of General Colour Rendering Index (CRI) $R_a \geq 60$ are used. Of the 5 million street lighting luminaires in the UK, approximately 4.5 million use High-Pressure Sodium (HPS) or Low-Pressure Sodium (LPS) lamps, selected for their high luminous efficacy and long life despite poor colour rendering performance. The trade-off between CRI and illuminance is used to support the installation of lamps such as Metal Halide (MH), which have a higher colour rendering index than sodium lamps but generally a lower luminous efficacy; the illuminance reduction offsets the lower efficacy and hence offsets an increase in overall energy consumption.

The decision to include an optional reduction of one S-class in illuminance was drawn from the professional judgement of practising lighting engineers. To encourage widespread use of the trade-off there is a need to determine whether it is supported by research evidence. The first stage of this process reviewed previous studies[3]. It was concluded that further evidence is required to confirm the effect of the spectral power distribution (SPD) of lamps that are used for street lighting on brightness and visual performance. This article discusses the results and implications of visual performance tests carried out to expand the body of evidence. A second paper discusses the results of the brightness investigation[4].

Pedestrians are faced with many different visual performance tasks, ranging from the essential, such as recognising 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[5]. Most such tasks first require off-axis detection followed by the use of the fovea to see detail, which can be characterised by measures of visual acuity and contrast sensitivity, and the ability to discriminate colours, which can be characterised by measures such as the accuracy of colour naming. If the trade-off between illuminance and CRI is adopted, then MH lighting at the lower illuminance needs to produce the same, or better, visual acuity, contrast sensitivity, colour naming ability and off-axis detection than HPS lighting at the higher illuminance if it is to be considered as providing acceptable lighting for pedestrians.

Fotios, Cheal & Boyce[3] reviewed previous studies of visual performance carried out under mesopic conditions. Two recent studies[6,7] suggested that SPD does not affect achromatic, foveal acuity. One of these[6] used a single fluorescent lamp with a series of filters to vary SPD rather than compare actual lamps used for street lighting. Two earlier studies[8,9] had hinted that SPD may affect acuity although they offer insufficient information to justify this conclusion. Previous acuity studies have used achromatic targets but real tasks may include some chromatic clues to identification. It was therefore concluded that further evidence is needed of the effect of SPD on visual acuity of foveal achromatic and chromatic targets in mesopic conditions. There is evidence that SPD does affect contrast threshold detection if the task extends beyond the fovea or is observed off-axis, but that SPD does not affect foveal tasks[7,10]. Since there is only limited evidence for this some confirmation is desirable. Two studies[7,11] found that at mesopic levels colour naming accuracy improved as the illuminance on the colours increased and also that MH and Compact Fluorescent (CFL) lamps permit more accurate colour naming than does HPS, which in turn offers more accurate colour naming than does LPS. Reaction time is considered to be important for pedestrians because it contributes to the speed with which an object, initially observed in the peripheral field, is noticed and hence transferred to the fovea for detailed inspection. Previous studies[10,12] demonstrate that in mesopic conditions lamp spectrum does not affect reaction times if the target stimulates only the fovea. 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: a MH lamp will permit a shorter reaction time than HPS of equal luminance, or similarly the MH needs a lower luminance to give the same reaction time as HPS. Studies of realistic tasks reveal a wide range of effects, with some tasks showing that SPD does affect performance but others showing no difference[7,13,14]. The problem with such studies is that the conclusions to be drawn from them depends on the nature of the tasks, specifically, the balance between on- and off-axis activity, how close the performance is to threshold, and the magnitude of the visual component of the overall task. Further evidence is needed to confirm the effect of SPD on visual performance in the real world.

This paper addresses two questions:

1. Does lamp SPD affect foveal visual performance at mesopic levels?
2. If the trade-off between illuminance and lamp SPD is applied, what are the implications for realistic pedestrian visual tasks?

2. Test Method

Foveal visual performance was measured using Landolt ring charts fixed to the rear walls of juxtaposed booths also used for brightness assessments[4]. During visual performance tests only one of the two booths was illuminated. An example of the achromatic acuity test chart is shown in Figure 2. The charts were printed on grey paper, having an approximate reflectance r = 0.20 similar to the reflectances of the interior surfaces of the booths, to ensure that task background luminance remained in the mesopic region. Participants were seated approximately one metre in front of the booths and this gave a viewing distance of approximately 1600mm from the participants eyes to the test chart. The lamps were fitted behind the booths and hence could not be seen directly. Light was directed into the booths using a light pipe, in which an iris damper was installed to permit mechanical dimming. Measurements of the spatial distribution of luminance confirmed that changes in the type of light source and test illuminance did not cause significant differences in luminance distribution inside the booths.

Five lamps were used, as described in Table 1 and Figure 1. The lamps were used individually to produce illuminances of 2.0 lux, 7.5 lux and 15 lux as measured at the centre of the floor of the booth, these being the top, middle and bottom of the S-series of lighting classes. At these three test illuminances, the rear wall of the booth had mean luminances of 0.11 cd/m^2, 0.39 cd/m^2 and 0.78 cd/m^2, and the background of the test charts had mean luminances of 0.07 cd/m^2, 0.25 cd/m^2 and 0.50 cd/m^2. There was a decrease in luminance from the top to bottom of the test charts – for the chart of mean luminance 0.25 cd/m^2 this ranged from 0.32 cd/m^2 at the top row of Landolt rings to 0.19 cd/m^2 at the bottom row. This range was the same for all lamps and test illuminances. At a given height, the rear wall of the booth and test chart had approximately the same luminance.

Achromatic acuity was measured using a chart of black Landolt rings of constant contrast (C=0.90) but of decreasing size (gap size range of 8.5 minutes of arc to 0.7 minutes of arc at the test distance), each row being 0.1 log units smaller than the row above, which is the same progression as used in the Bailey-Lovie chart[15]. There were five Landolt rings on each of the ten rows. Contrast threshold was measured using an achromatic chart of Landolt rings of constant size (gaps subtended 4.3 min.arc at the test distance) but of decreasing contrast (contrast range = 0.90 to 0.04, as measured when illuminated by the CFL lamp), each row having a contrast 0.15 log units lower than the row above, which is the same progression as in the Pelli-Robson chart[16]. There were five Landolt rings on each of the ten rows. A recent study of test charts found that Landolt ring tasks provided the highest repeatability and the best between-groups discrimination, and was thus determined to be the preferred clinical test for comparing contrast sensitivity under different lighting conditions[17].

Acuity was also measured using charts of coloured Landolt rings, these being red (x=0.417, y=0.315)[†], green (x=0.296, y=0.491) and blue (x=0.212, y=0.226) on separate cards. The charts were designed to achieve a luminance contrast of zero, as measured under the VeriVide D65 daylight simulating fluorescent lamp, thus to identify the contribution of chromatic contrast to visual acuity. The actual luminance contrasts achieved were 0.01 for the red chart, 0.04 for the green chart, and 0.05 for the blue chart. These charts followed the same design as did the achromatic acuity chart, other than the colour of the Landolt ring. The lowest test illuminance of 2.0 lux was not used with the coloured Landolt ring charts because pilot tests revealed that not even the top line of these charts was legible at this level. In following discussions these are referred to as the chromatic acuity tests.

Test participants were instructed to name the position of the gap in the Landolt ring (either left, right, top or bottom), attempting any they were uncertain of, and continuing down the chart until they could no longer distinguish the Landolt rings. Performance was scored and analysed as the number of gap orientations correctly identified, as was done in previous work[7,18]. There was no time constraint, and the time taken to complete the task was not recorded. Achromatic acuity and contrast detection tests were run concurrently with 15 younger participants (age range 18-54 years, only one of whom was over 44 years, and five were female) and 15 older participants (age range 60-85 years of whom 11 were female). Chromatic acuity tests were completed by 15 younger participants (age range 18-54 years, only one of whom was over 44 years, and nine were female) and 12 older participants (age range 60-85 years, including nine females). All observers were colour-normal according to the Ishihara test. For each test, several variations of each chart were used and the order of presentation of the different achromatic or colour charts was randomised. The location (left or right booth) and sequencing of each lighting condition (lamp type and illuminance) was counterbalanced between observers. Twenty minutes dark adaptation was allowed at the beginning each series of tests.

3.1 Test Results: Achromatic Acuity

Figure 3 and Table 2 show the mean results of the thirty participants. Analysis using a three-factor mixed ANOVA shows that the results were not significantly affected by type of light source. There is a significant effect of luminance ($p<0.001$), with lower chart luminances giving lower acuity, and a significant effect of age ($p<0.01$), with older participants scoring lower than younger participants ($p<0.01$). These results agree with previous studies whose results suggest that SPD does not affect performance of a foveal, achromatic acuity task and that MH and HPS lamps will offer equal visual performance at the same luminance[6,7]. A previous study[8] had reported that LPS

[†] *Chromaticity as measured under a VeriVide D65 daylight simulating fluorescent lamp.*

lamps can produce better visual acuity than high pressure mercury fluorescent lamps but offered insufficient information to justify this conclusion - the current results found that the LPS lamp offers the same visual acuity as HPS, MH and CFL lamps. The ANOVA suggests significant interaction between participant age and luminance ($p<0.001$) but no significant interaction between age and SPD or illuminance and SPD. The older age group display a greater decrease in acuity as the luminance reduces than do the younger age group, as is expected from previous work[19].

3.2 Test Results: Contrast Detection Threshold

Figure 4 and Table 3 show the mean results of the thirty participants. Analysis by a 3-factor mixed ANOVA shows three significant effects:

- Lamp type ($p<0.01$); further analysis using paired *t*-tests indicates that the LPS lamp yields a higher number of correctly read Landolt rings than the other lamps ($p<0.05$). The HPS, CFL, MH1 and MH2 lamps yield similar frequencies of Landolt ring identification.
- Luminance ($p<0.001$); at lower chart luminances, fewer Landolt rings were correctly identified.
- Age of test participant ($p<0.05$); older participants scored lower than younger participants.

These results agrees with a previous study using a small (12 min. arc) foveal task, which also found that the number of Landolt rings correctly identified increased with increasing chart background photopic luminance but that there was no difference between MH and HPS lamps[7]. The ANOVA does not identify any significant interactions between age, luminance and SPD in the current results.

The results reveal a significantly higher sensitivity to luminance contrast under the LPS lamp than under the HPS, CFL, MH1 and MH2 lamps. One possible explanation is the actual luminance contrast of the target under the different lamps. The luminance contrast of the test chart was established under the CFL lamp. If the LPS lamp produced a higher luminance contrast than the other lamps then this would explain why LPS lighting produced better Landolt ring identification. Table 4 shows the luminance contrast of the third row of Landolt rings as measured under the different test lamps. It can be seen that the LPS lamp does not give the higher luminance contrast and thus this does not explain the better visual performance found under the LPS lamp.

A second possible explanation is the variable impact of chromatic aberration with light sources of different SPD. Because the refractive index of the human lens varies with wavelength there is no possibility that the mixed rays from a polychromatic stimulus can all be optimally focused upon the retina[20]. This suggests that targets seen under the near-monochromatic light from LPS will be in sharper focus than targets seen under light from the MH1, MH2, CFL and HPS lamps which are polychromatic.

3.3 Test Results: Chromatic Acuity

Figure 5 and Table 5 show the mean number of Landolt Rings correctly read by the 27 older and younger participants for the chromatic acuity charts. A four-factor mixed ANOVA shows significant effects of luminance ($p<0.001$), light source type ($p<0.001$), target colour ($p<0.001$) and age of participant ($p<0.01$) with older people tending to have a poorer visual acuity than younger participants. For all lamp types, the mean number of correctly read Landolt rings was higher at the higher illuminance. Further analysis using a three-factor ANOVA applied separately to the results gained from each target colour confirms that luminance, light source and age of participant each have a significant effect ($p<0.01$) on the results. Analysis by paired *t*-test suggest that target colour has a significant effect on Landolt ring identification in all cases except (i) there is no difference in acuity for the green and blue targets under lamp MH2 at both test illuminances, and (ii) there is no difference in acuity for red and blue targets under HPS at the higher test illuminance.

The four-factor ANOVA reveals notable interactions between light source and target colour ($p<0.001$). These may be caused by differences in luminance contrast. The charts were designed to offer minimal luminance contrast so that legibility was a function primarily of chromatic contrast. This was measured under the VeriVide D65 fluorescent lamp, but between the different test lamps there is variation in luminance contrast of the target, as shown in Figure 6. With the red chart, the MH1 lamp gave significantly better performance than the other lamps at the higher illuminance ($p<0.01$) and the LPS lamp gave significantly poorer performance ($p<0.001$) at both illuminances. Figure 6 shows that the red Landolt rings have their highest luminance contrast under the MH1 lamp and their poorest luminance contrast under the LPS lamp. With the green chart, the CFL lamp gave a significantly better performance than the other lamps at both illuminances ($p<0.01$). Figure 6 shows that the green Landolt rings have their highest luminance contrast under the CFL lamp. With the blue chart, the HPS lamp gave significantly better performance than the other lamps at the higher illuminance ($p<0.01$); the MH2 lamp gives poorer performance than the other lamps at both illuminances but not significantly so. Figure 6 shows that the blue Landolt rings have their highest luminance contrast under the LPS and HPS lamps and their lowest luminance contrast under the MH2 lamp. Thus the interaction between light source and target colour can be explained by residual luminance contrast.

The four-factor ANOVA reveals notable interactions between light source and light level ($p<0.01$). No consistent trends have been identified but there are some interactions observable in Figure 5.

For example, consider the lamp yielding the highest number of correctly read Landolt rings: in the red and blue targets at the lower luminance this highest scoring lamp is not significantly better than the next best lamp, but at the higher luminance there is a significant difference ($p<0.01$) between them. Consider the relative performance of the MH1 lamp compared to the other lamps; in both the red and green charts its relative position changes between the two luminances. In the red chart, performance under the MH1 lamp is not significantly different to that obtained with the other lamps at the lower luminance but allows significantly higher performance ($p<0.01$) at the higher luminance; in the green chart the MH1 yields the lowest performance at the lower luminance, lower than that of the LPS, but at the higher luminance the MH1 yields a higher performance than the LPS, although at both luminances the differences are not significant. Further testing is needed to investigate these interactions.

3.4 Test Results: Colour Naming

A colour naming task was carried out concurrently with semantic rating tests[4] applied to the lighting in a large room of dimensions 10.5m deep, 6.1m wide and 5.7m high. This was carried out under the same five light sources (Table 1) at two mean illuminances, approximately 2.0 lux and 15.0 lux as measured at floor level. The test was carried out partly to expand the data available[7,11] and partly to provide a task to occupy the time (five minutes for chromatic adaptation) between participants entering the test room and carrying out the semantic rating test. Twenty minutes dark adaptation was allowed at the beginning each series of tests. Whilst the lighting conditions were changed, the illuminance or light source or both, the participants waited in an adjoining room. This waiting room was illuminated by a VeriVide D65 lamp with room surfaces of luminance lower than $3cd/m^2$. Upon entering the test room a further two minutes were allowed before the colour naming test was carried out, this being to allow at least 90% of chromatic adaptation to be reached, as suggested by evidence from colour appearance studies[21].

Participants were asked to name the colour of a series of surfaces, presented individually, choosing from a list of eight possible names: red, blue, green, yellow, purple, orange, light-grey and dark-grey. There are two classes of colour appearance: surface-colour perception, which refers to the perception of an object colour as an attribute of the object surface, and apparent-colour perception, which refers to a simple apparent colour[22]. In the current work, participants were asked to state which colour sample it was, i.e. the surface colour rather than the apparent colour.

Eight colour squares from the Gretag Macbeth colour checker chart were used: red, blue, green, yellow, purple, orange, light-grey (neutral 8), dark-grey (neutral 5). The samples were surrounded by a mask of grey paper (r = 0.20), and subtended an image of approximately 4.5

degrees at the participant's eye at the approximate 0.5 metre viewing distance. Luminance of the background was approximately 0.13 cd/m^2 and 1.33 cd/m^2 at the two test illuminances. Ten colour samples were shown in a random order under each condition (lamp type and illuminance), these being all eight colour squares shown at least once and two samples were shown twice. This was done to avoid participants simply stating the last remaining colour on the list when nearing the end of the presentation series. The second responses for the two colour samples that were shown twice were recorded but are not included in the analysis.

The results are shown in Figure 7 and Table 6. As expected, the LPS lamp offers poor colour naming accuracy. The other lamps produced a colour naming accuracy approaching 100%, with even the HPS lamp, which has a relatively poor CRI, giving a colour naming accuracy of more than 85%. Three-factor mixed ANOVA shows significant effects of light source ($p<0.001$), age ($p<0.001$) and luminance ($p<0.05$) and significant interaction between lamp and luminance ($p<0.01$). Paired *t*-tests show no significant difference between performance under CFL, MH1 and MH2, and this group offers better colour naming than does the HPS ($p<0.01$). The age of participants caused a significant effect only under the MH1, MH2 and CFL lamps and only at the lower illuminance; in these cases, the *t*-tests indicate the colour naming accuracy of the older age group is significantly lower than that of the younger age group ($p<0.05$). Figure 7 shows a trend for colour naming accuracy to decrease at lower illuminance under all lamp types. According to paired *t*-tests colour naming accuracy at the lower illuminance is significantly reduced under the HPS ($p<0.001$), CFL ($p<0.05$) and MH1 ($p<0.01$) but under the LPS and MH2 lamps there is no change with luminance. These results agree with previous studies[7,11] which report the same relationship between lamp type and colour naming accuracy and that this accuracy decreases as luminance decreases toward scotopic levels.

It may be surprising that colours could be recognised at all under LPS lighting since the light is near-monochromatic. The forced choice of colour from a list of eight options means that a score of 12.5% accuracy is expected due to chance. Furthermore, it is expected that participants gained some clue to the colour of the target from its luminance contrast to the background grey mask, this contrast not being matched between the targets used. Chen[11] also found a colour naming accuracy of approximately 30% to 40% under LPS lighting.

3.5 Test Results: Summary

MH lighting at the lower illuminance needs to produce the same, or better, visual acuity, contrast sensitivity, colour naming ability and off-axis detection than HPS lighting at the higher illuminance if it is to be considered as providing acceptable lighting for pedestrians. It was found that the performance of foveal visual acuity, contrast sensitivity and colour naming tasks will decrease as illuminance is reduced. For achromatic foveal visual acuity and contrast sensitivity there is no significant difference between the HPS and MH lamps and hence lamp type does not offset the reduction of acuity at lower illuminance. For the acuity of coloured targets there is a significant effect of lamp type that interacts with the colour of the target: lamp SPD can improve acuity but this depends on the colour of the target. Colour naming accuracy is affected by lamp type, with the MH lamps offering more accurate colour naming than the HPS lamp; colour naming accuracy under MH lamps at approximately 2.0 lux is similar to colour naming accuracy under HPS at approximately 15.0 lux. From previous work[12] it can be seen that in mesopic conditions the reaction time to an off-axis target increase as luminance decreases but that MH lighting produces a shorter reaction time than does HPS lighting; at 0.1 cd/m^2 the reaction time under HPS is matched by the MH at 0.052 cd/m^2. Therefore, the results of laboratory tests suggest that in some cases MH lighting at the lower illuminance does not produce the same visual performance as HPS lighting at the higher illuminance.

4. Real Visual Tasks

If lighting is designed to take advantage of the illuminance reduction permitted in BS5489-1:2003[2] by using lamps of $R_a \geq 60$ there will be a reduction in visual performance, in particular, achromatic foveal visual acuity and contrast detection threshold will deteriorate. Whether this leads to a significant reduction in the performance of real tasks depends on the nature and magnitude of the visual component of the task. Three key visual tasks for the pedestrians are orientation, detection of obstacles and identification of persons[23].

4.1 Orientation

Orientation within the environment is a complex process involving parameters like expectation, experience and memory. A person visiting a residential area for the first time will orientate themselves mainly by way of large objects, such as a tall building, and once in the vicinity of their destination will expect to read street names[5]. For large objects, the reduction in visual acuity will have a negligible effect. For smaller objects such as street signs, a reduction in visual acuity and contrast detection suggests a reduction in legibility, but the pedestrian is probably able to offset this by moving closer to the task and by using supplementary orientation objects. For objects which offer chromatic contrast against their background, lamps of $R_a \geq 60$ will improve visibility. The visual component is anyhow only part of the overall orientation task, and it is therefore expected that the reduction in on-axis visual acuity and contrast detection following the reduction in illuminance is not sufficient to significantly affect orientation.

4.2 Obstacle Detection

An obstacle is an approaching object or irregularity that may cause a pedestrian to trip, or is not noticed in time to avoid collision. This might be a small discontinuity such as a raised paving slab, or a large object such as an item of street furniture that is not seen because the pedestrian is not paying attention and its presence is unexpected. Lighting which improves the contrast of an object against its background will improve the rate of detection. From Lewis's[10] results it is expected that MH lighting will enable better contrast sensitivity and thus better detection than does HPS lighting for peripheral objects and large ($>2^{O}$) on-axis targets. This expectation is confirmed by Lingard & Rea[24] and Bullough & Rea[25] who found that SPD affected the detection of peripheral targets during simulated driving tasks, with a higher detection rate under MH than under HPS. Mulder & Boyce[26] examined the effect of SPD on the ability of pedestrians to move through an obstructed space, this being carried out to investigate interior emergency lighting and thus at lower luminances (near scotopic) than are usual in exterior lighting: they found that both luminance and SPD affected performance, with lighting of higher luminance and Scotopic to Photopic (S/P) ratio giving the faster speed of escape and the fewer collisions. Further work is needed to test whether MH lighting at a reduced illuminance offers the same obstacle detection ability as HPS lighting, using stimulus conditions appropriate for pedestrians. This might be done by investigating the effect of light source and luminance on the shape and size of the visual detection lobe for a fixed target. The visual detection lobe is the probability of detecting the presence of the target at various degrees off-axis in a single fixation pause[27]. Reducing illuminance is expected to reduce the peak of the lobe. Changing from HPS lighting to MH lighting having the greater short wavelength content and hence greater rod stimulation is expected to increase the width of the lobe. The lighting condition giving the greater area of visual detection lobe will allow the more effective visual search.

4.3 Identification of Persons

The effect of lighting conditions on facial recognition can be examined by comparing the distance at which a given level of facial recognition is achieved. Caminada & van Bommel[23] identified two critical distances for facial recognition: 4m, at which an alert subject can take evasive or defensive action; and 10m, the ideal distance at which facial recognition is made, being the transition between the *close* and *not-close* proximity zones. Bullimore, Bailey & Wacker[28] found significant correlation ($p<0.01$) between facial recognition distance and clinical tests of vision, these being contrast threshold, grating acuity, letter chart acuity and word reading acuity. Therefore, if the reduction in visual performance associated with a reduction in illuminance is known, the results of Bullimore *et al* can be used to predict the impact on facial recognition distance. This is shown in Table 7.

The reduction in visual acuity and contrast detection occurring when illuminance is decreased by one class of the S-series is determined by interpolation of the current experimental results. To match the data presented by Bullimore *et al*[28] the current results were drawn to show log Minimum Angle of Resolution (logMAR) and log Contrast Threshold, as shown in Figure 8. Best fit linear regression lines were drawn to fit the mean results from both age groups and all lamp types and this yields significant correlation ($p<0.01$) in both cases (visual acuity, $r^2=0.422$; contrast sensitivity, $r^2=0.486$).

Consider lighting designed to an average illuminance of 7.5 lux. If the S-series trade-off is adopted the design illuminance can be decreased to 5.0 lux. The differences in visual acuity and contrast detection threshold between these two illuminances can be found from Figure 8. Using the relationships between facial recognition distance and visual acuity, and between facial recognition distance and contrast detection threshold, as reported in Figure 4 from Bullimore *et al*[28] the changes in facial recognition distance resulting from the illuminance reduction were determined. To achieve the same degree of facial recognition at 5.0 lux as at 7.5 lux, Table 7 shows that the approaching person must now be closer, by up to 20%. The contrast detection threshold data predicts a greater reduction in facial recognition distance than does the visual acuity data. A similar reduction in facial recognition distance is found with the other S-series illuminance trade-offs.

However, this reduction may be counterbalanced by improvements in colour performance of the lamps to which the S-class trade-off is applied. The current work found that MH lighting permits significantly better colour naming accuracy than does HPS ($p<0.01$). Figure 7 shows that colour naming accuracy under MH and CFL lighting at 2.0 lux is slightly better than accuracy under HPS lighting at 15.0 lux. Two studies have investigated facial recognition ability under different light sources. Raynham & Saksvikrønning[13] found that at a semi-cylindrical illuminance of 1.0 lux, facial recognition was achieved at approximately 4.5m under lighting from compact fluorescent lamps but at approximately 3.0m under lighting from high pressure sodium lamps. Knight & van Kemenade[29] investigated identification using photographs of people, of average vertical illuminance 1.4 lux under MH lighting and 3.3 lux under HPS lighting. They found accurate facial identification was possible at a greater distance (6.6m) under the MH lighting than under the HPS lighting (5.4m) despite the lower vertical illuminance. Thus the reduction in visual acuity and contrast sensitivity resultant from a one S-class reduction in illuminance is at least partially offset by improvements in colour performance and the overall effect on facial recognition distance is not expected to be significant. Further work is needed to test this directly.

5. Conclusion

BS5489-1:2003[2] permits a reduced illuminance when using lamps of high Colour Rendering Index (R_a ≥60). This paper set out to compare visual performance under lighting of different SPD at mesopic conditions, with an emphasis on the comparison of MH and HPS lamps. This was done using clinical tests of visual performance at mesopic levels. It was found that achromatic foveal visual acuity and contrast threshold are not affected by lamp type but are affected by luminance – a reduction in luminance reduces visual performance. At lower luminances, colour naming accuracy decreases and off-axis reaction time increases, but these reductions are offset by lamp SPD with improved performance under MH lighting compared to HPS lighting. An analysis of the implications of these results for typical visual tasks carried out by pedestrians suggests that if MH lighting is used at one S-class illuminance lower than HPS lighting there will be no significant effect on facial recognition and visual orientation tasks. Further work is needed to investigate implications for obstacle detection.

Additional studies are needed to extend the investigation of lighting for pedestrians. Firstly, visual performance tests should be carried out in real (outdoor) situations to determine the validity of extending laboratory data. Secondly, this study has compared relative values, i.e. a comparison of visual performance at different illuminances. It does not reveal whether those illuminances are appropriate for the purpose for which the lighting was installed. Further work is needed to investigate whether the absolute illuminance values for pedestrian lighting, as prescribed in BS EN 13201-2:2003[1] are appropriate, and this demands, initially, discussion of the tasks that are important to pedestrians. Some initial work has been carried out[30] comparing, under different illuminances, distances for facial recognition, avoidance of stationary obstacles, avoidance of collision with on-coming pedestrians, and minimum distance for comfort, although the small sample sizes used and the absence of complete statistical data does not yet enable firm conclusions to be drawn.

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Lamp type		CCT (K)	CRI (R_a)
LPS	SOX Pro 35W		
HPS	SON-T Pro 70W	2000	25
CFL	Master PL-L 55W/830	3000	82
MH1	Master City White CDO-TT 70W/828	2800	83
MH2	Master Colour CDM-T 70W/942	4200	92

Table 1 Description of lamps used in visual performance tests. CCT and CRI are as reported in manufacturer's literature.

Illuminance (lux)	Lamp	All participants (N=30)		Older participants (N=15)		Younger participants (N=15)	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
2.0	LPS	24.33	5.44	22.80	5.47	25.87	4.96
	HPS	24.17	4.42	22.73	4.61	25.60	3.70
	CFL	23.77	5.34	21.20	4.86	26.33	4.50
	MH1	24.00	5.05	22.00	5.47	26.00	3.63
	MH2	23.43	4.34	21.40	3.93	25.47	3.74
7.5	LPS	32.13	5.51	29.47	5.14	34.80	4.48
	HPS	31.83	4.55	30.40	5.10	33.27	3.36
	CFL	31.80	5.93	29.07	5.80	34.53	4.66
	MH1	31.13	5.20	29.13	5.45	33.13	4.05
	MH2	31.40	4.58	29.40	4.19	33.40	4.05
15.0	LPS	35.30	5.94	32.80	6.59	37.80	3.82
	HPS	34.33	6.82	31.13	7.69	37.53	3.67
	CFL	35.07	5.62	32.47	5.94	37.67	3.77
	MH1	35.10	6.17	31.27	5.72	38.93	3.75
	MH2	35.40	5.57	32.33	5.34	38.47	3.83

Table 2 Results of achromatic visual acuity tests, the mean number of Landolt rings correctly identified under each lighting condition. The table shows the mean results for all participants and subsequently for the older and younger age groups.

Illuminance (lux)	Lamp	All participants (N=30)		Older participants (N=15)		Younger participants (N=15)	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
2.0	LPS	14.93	4.97	12.87	4.77	17.00	4.24
	HPS	13.53	5.72	11.13	5.63	15.93	4.71
	CFL	13.20	6.47	10.07	5.59	16.33	5.73
	MH1	14.03	5.17	11.27	4.70	16.80	4.02
	MH2	13.30	5.72	10.67	5.69	15.93	4.37
7.5	LPS	23.93	5.62	21.60	6.25	26.27	3.64
	HPS	22.53	6.06	20.07	7.14	25.00	3.22
	CFL	22.30	5.95	20.33	6.23	24.27	4.92
	MH1	22.33	5.61	20.13	6.41	24.53	3.50
	MH2	23.33	5.76	21.80	6.50	24.87	4.41
15.0	LPS	28.37	5.44	26.60	5.85	30.13	4.33
	HPS	26.63	5.31	24.80	6.26	28.47	3.24
	CFL	26.57	5.73	24.40	6.52	28.73	3.70
	MH1	26.97	5.74	24.47	6.30	29.47	3.70
	MH2	27.03	5.53	24.60	5.26	29.47	4.66

Table 3 Results of achromatic contrast detection threshold tests, the mean number of Landolt rings correctly identified under each lighting condition. The table shows the mean results for all participants and subsequently for the older and younger age groups.

Lamp	**Luminance contrast**
LPS	0.38
HPS	0.42
CFL	0.40
MH1	0.38
MH2	0.38

Table 4 Luminance contrast of Landolt Rings on the contrast threshold detection test chart, as measured under the individual lamps. These data are for the third row of Landolt rings; the rank order of luminance contrast is similar for the other rows of Landolt rings.

Illuminance (lux)	Lamp	All participants (N=27)		Older participants (N=12)		Younger participants (N=15)	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
		Red Landolt rings					
7.5	LPS	13.26	4.09	11.67	3.99	14.53	3.70
	HPS	21.00	5.54	18.25	5.63	23.20	4.37
	CFL	21.78	5.81	19.08	6.46	23.93	4.12
	MH1	21.78	5.20	19.58	4.73	23.53	4.88
	MH2	21.04	5.43	18.67	5.60	22.93	4.45
15.0	LPS	17.26	4.56	14.58	3.73	19.40	4.00
	HPS	24.78	6.36	21.17	6.36	27.67	4.66
	CFL	25.07	5.75	21.92	6.14	27.60	3.88
	MH1	27.22	5.92	23.50	5.12	30.20	4.71
	MH2	25.11	5.69	22.17	5.98	27.47	4.13
		Green Landolt rings					
7.5	LPS	12.00	4.06	9.75	4.32	13.80	2.71
	HPS	13.07	4.45	10.67	4.61	15.00	3.20
	CFL	16.67	6.22	13.83	5.30	18.93	5.97
	MH1	10.70	5.38	7.25	2.62	13.47	5.43
	MH2	12.37	5.83	9.50	4.84	14.67	5.53
15.0	LPS	15.56	4.25	13.08	3.66	17.53	3.59
	HPS	18.26	4.90	16.00	5.21	20.07	3.77
	CFL	20.67	6.25	17.50	5.33	23.20	5.75
	MH1	16.33	5.74	13.92	3.93	18.27	6.21
	MH2	16.63	6.25	13.25	4.92	19.33	5.87
		Blue Landolt rings					
7.5	LPS	18.74	4.87	15.83	3.56	21.07	4.52
	HPS	19.22	4.68	16.83	4.83	21.13	3.54
	CFL	13.70	5.20	11.67	5.56	15.33	4.24
	MH1	16.22	5.00	13.67	4.87	18.27	4.07
	MH2	12.89	4.28	11.67	4.52	13.87	3.81
15.0	LPS	22.48	5.53	19.50	4.59	24.87	5.03
	HPS	24.74	5.21	22.17	5.24	26.80	4.17
	CFL	18.19	5.28	15.50	5.80	20.33	3.61
	MH1	21.07	4.91	18.75	4.49	22.93	4.40
	MH2	17.48	5.44	14.67	5.95	19.73	3.68

Table 5 Results of chromatic acuity tests, the mean number of Landolt rings correctly identified under each lighting condition. The table shows the mean results for all participants and subsequently for the older and younger age groups.

Illuminance (lux)	Lamp	All participants (N=47)		Older participants (N=18)		Younger participants (N=29)	
		%	Std. Dev.	%	Std. Dev.	%	Std. Dev.
2.0	LPS	41	28	40	28	42	28
	HPS	85	15	84	20	86	13
	CFL	96	7	92	13	99	4
	MH1	96	6	92	8	98	5
	MH2	98	4	95	10	99	2
15.0	LPS	41	28	38	30	44	27
	HPS	94	4	92	7	96	4
	CFL	99	2	98	3	100	1
	MH1	100	1	100	0	100	1
	MH2	98	3	97	4	99	2

Table 6 Results of colour naming tests, the mean percentage of colour samples correctly identified under each lighting condition. The table shows the mean results for all participants and subsequently for the older and younger age groups.

Critical facial recognition distance	(m)	**4.0**		**10.0**	
	(log m)	0.602		1.0	
Clinical test of visual performance		Visual Acuity	Contrast Threshold	Visual Acuity	Contrast Threshold
Reduction in visual performance (from current data)		0.045 logMAR	0.081 logCT	0.045 logMAR	0.081 logCT
Reduction in recognition distance (from Bullimore *et al* [28])	(log m)	0.06	0.10	0.06	0.10
Facial recognition distance after reducing illuminance by one S-class	(log m)	0.542	0.502	0.94	0.90
	(m)	**3.48**	**3.18**	**8.71**	**7.94**

Table 7 Prediction of the reduction in facial recognition distance resulting from a reduction in design illuminance equivalent to one class of the S-series. *Critical* facial recognition distance is as suggested by Caminada & van Bommel[23]. The reduction in visual performance is predicted using the results of visual acuity and contrast detection threshold in Figure 8.

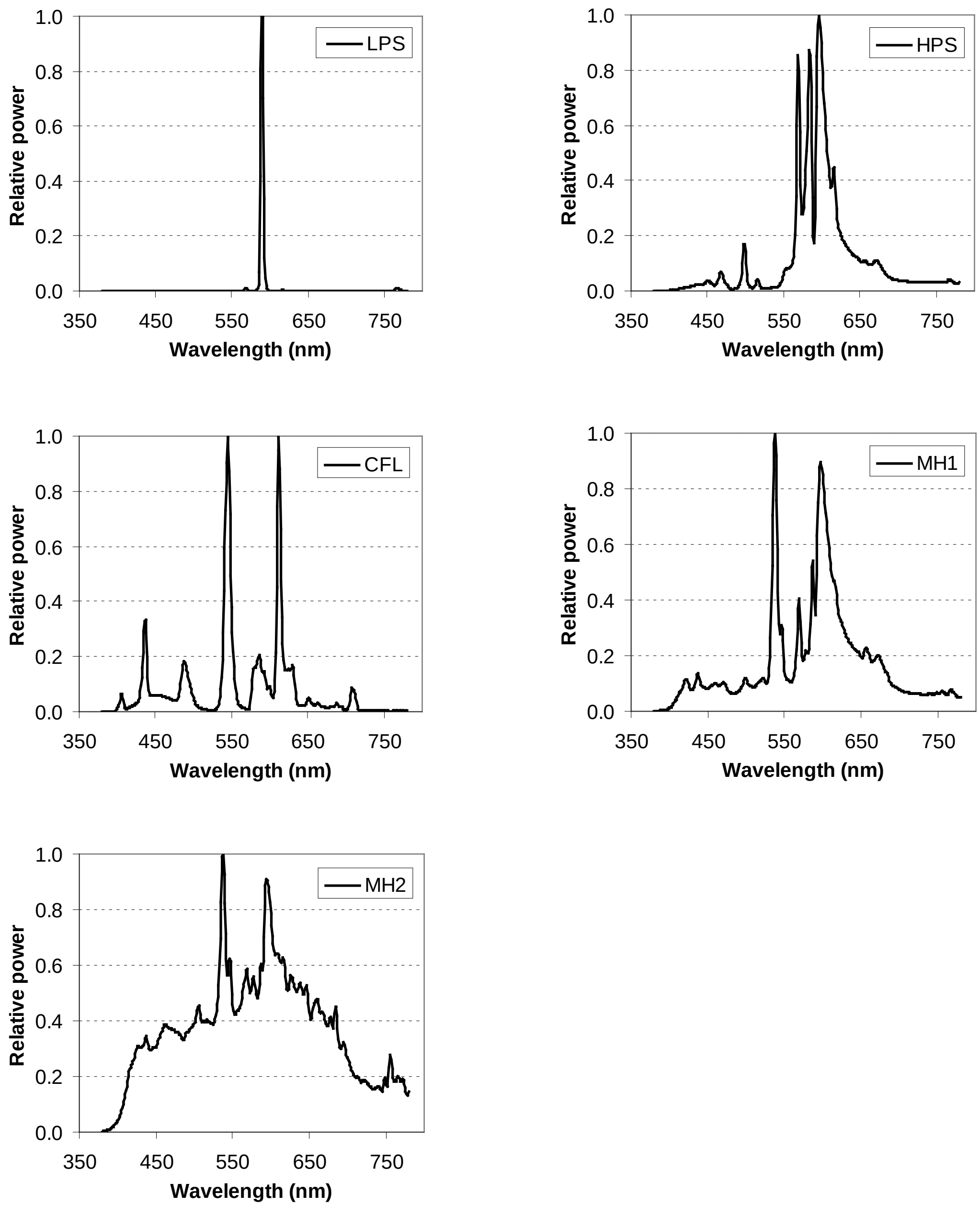
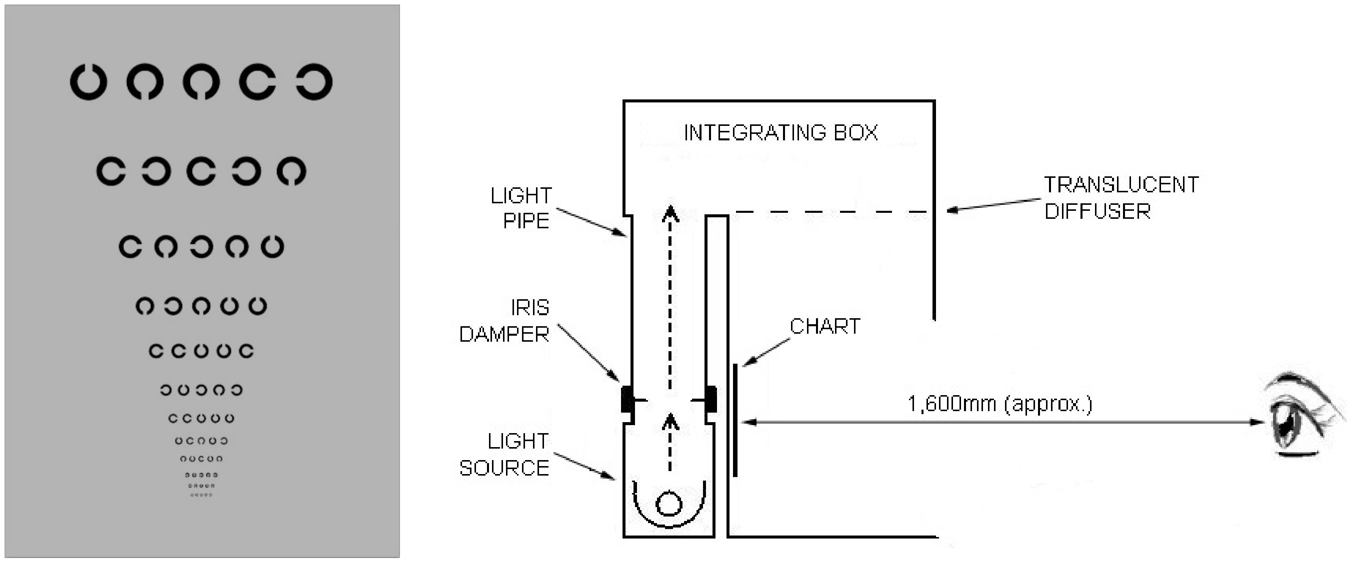


Figure 1
Spectral Power Distributions of the experimental lamps, normalised to a peak relative power of unity. SPD measured using a Konica-Minolta CS1000a spectroradiometer.



(a) (b)

Figure 2
Visual performance test charts. (a) Example of the Landolt ring chart used to test achromatic visual acuity. (b) Cross section through the lighting booth. The acuity and contrast detection test charts were presented on the rear wall of the side-by-side booths, as were used also to investigate brightness[4]. For the visual performance tests, only one booth was illuminated.

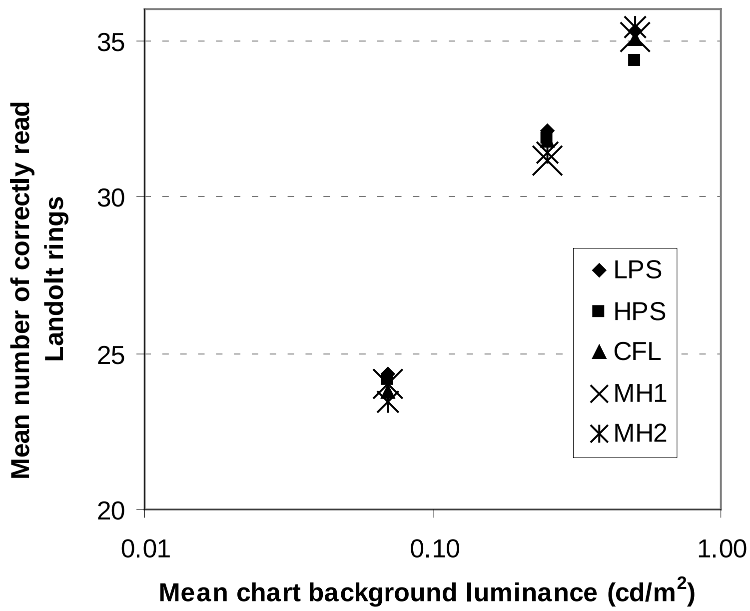


Figure 3

Results of achromatic visual acuity test - mean number of correctly read Landolt rings under each lamp and luminance combination. These are the mean results of the older and younger participant groups combined.

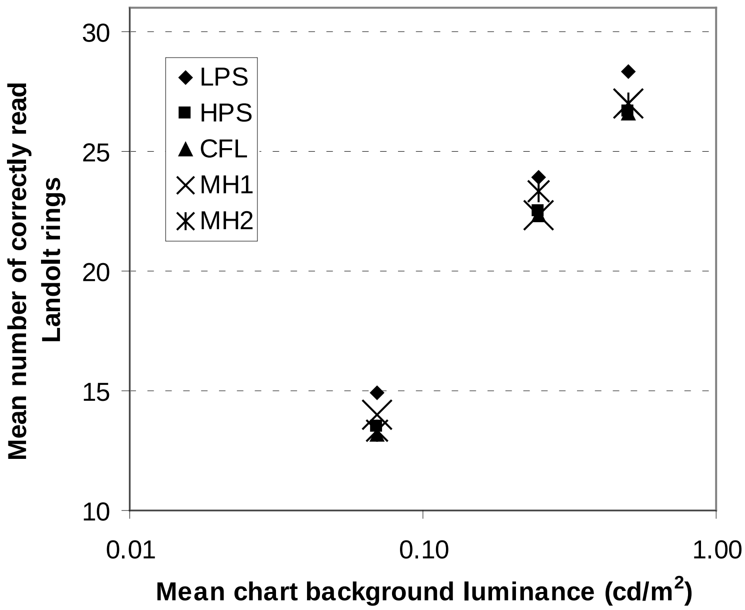


Figure 4

Results of contrast threshold test - mean number of correctly read Landolt rings under each lamp and luminance combination. These are the mean results of the older and younger participant groups combined.

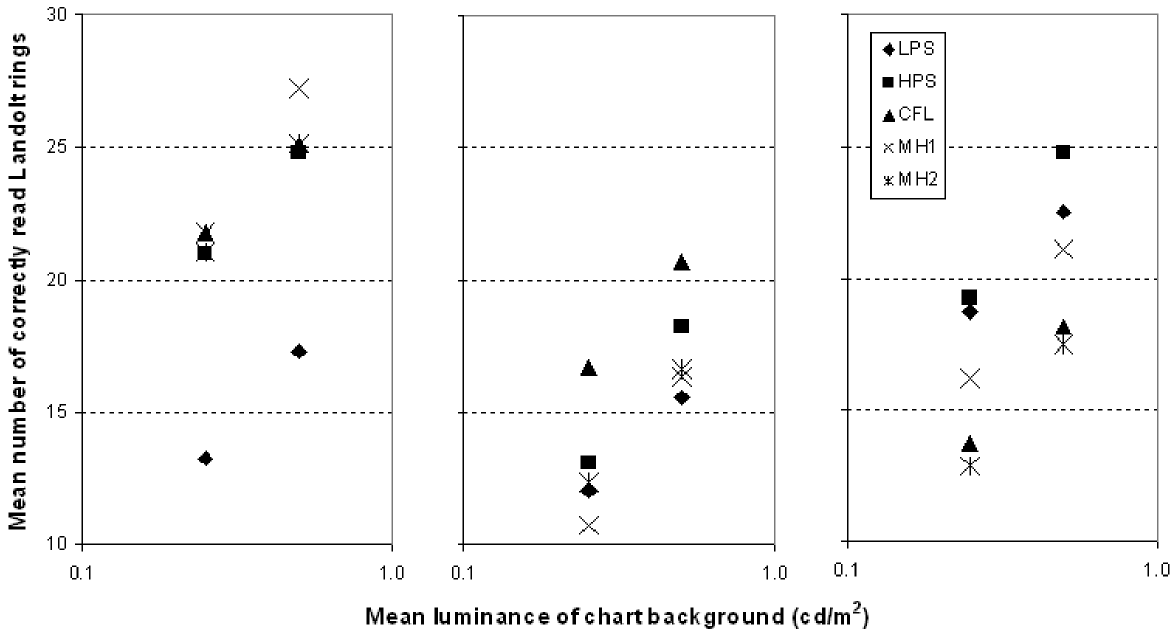


Figure 5

Mean acuity scores with chromatic Landolt ring tests. The target colours are (left to right) red, green and blue. These are the mean results of the older and younger participant groups combined.

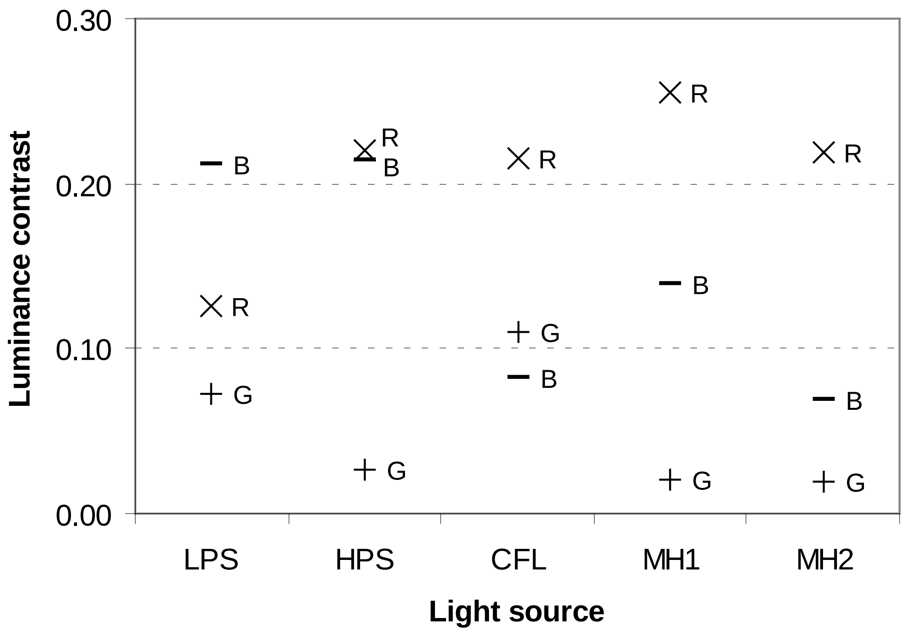


Figure 6

Luminance contrast of coloured Landolt rings under the individual test lamps. B = blue Landolt rings; R = red Landolt rings; G = green Landolt rings.

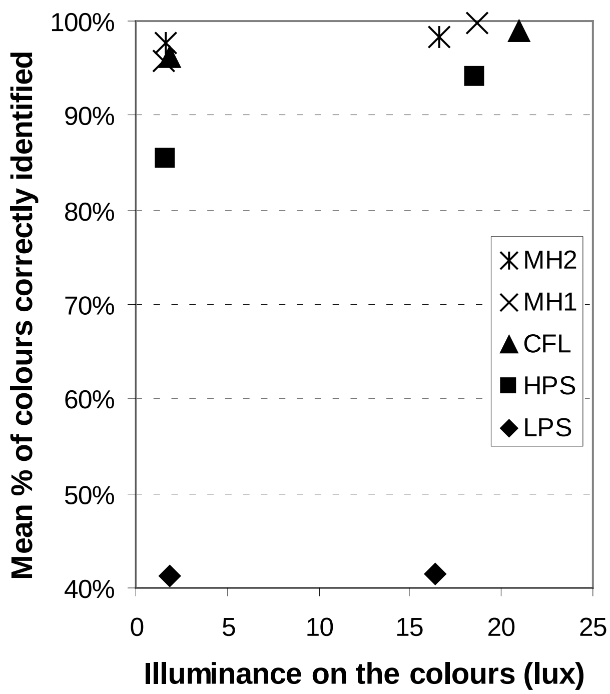
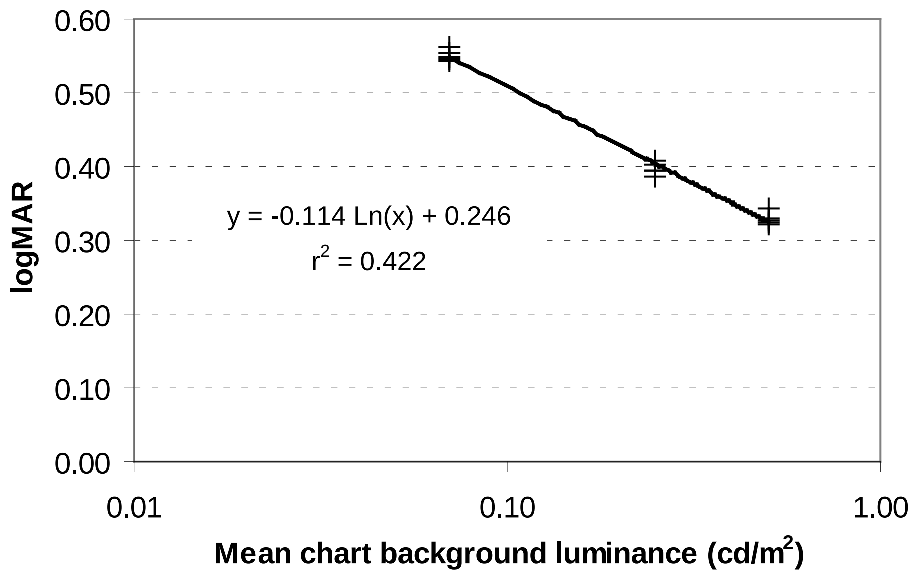


Figure 7

Results of the colour naming test. These are the mean results of the older and younger participant groups combined.



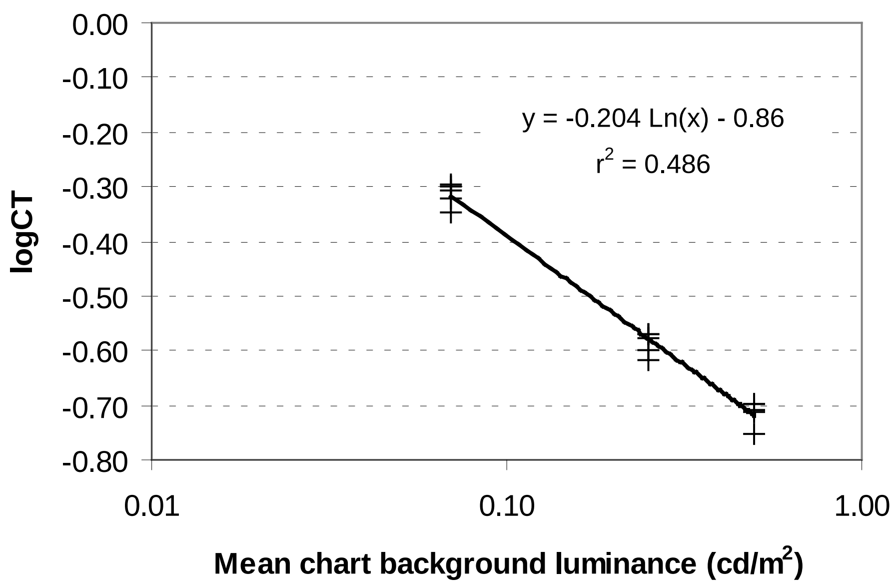


Figure 8

Visual performance results. These are Figures 3 and 4 redrawn with alternative y-axes to enable comparison with facial recognition data. The best fit lines are drawn to fit the results of all participants under all lamps at each test luminance: the data points are the mean values of visual performance under the different lamps.