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A comparison of traditional and high colour temperature lighting on the near acuity of elementary school children

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The near visual acuity (400 mm distance) of 27 children aged 10–11 years old was measured by a licensed optometrist under two common fluorescent lamps of CCT 3600 K and 5500 K. Acuities were measured for three lighting conditions, either both lamps providing equal task luminance or a condition where the task and room luminance from the 5500 K lamps was set 50% lower. For the equal luminance condition, the results showed visual acuity was significantly better ($P < 0.001$) under the higher CCT lamp with 24 of 27 children having better acuity. Paired *t*-tests comparing the lower luminance condition showed significantly less acuity for the 5500 K lamps at the lower luminance, but no significant difference between the 3600 K lamps at the higher luminance compared with the 5500 K lamps at the lower luminance.

1. Overview

Past studies have shown that varying the ambient light spectrum of essentially white light but at fixed photopic levels affects the visual acuity of adults of all ages. In this study those results including the vision and energy savings implications are extended to young children.

Near visual acuity (obtained by utilizing Bailey-Lovie letter charts adjusted for the typical reading condition of 400 mm distance) of 27 children aged 10–11 years old was measured by a licensed optometrist under ceiling lighting provided by two different but readily available fluorescent lamps. The measurements were obtained in a room on the school premises outfitted with specially designed lensed luminaires that simultaneously housed both lamp types whose light levels were separately controllable by a wall-mounted switch/control.

One lamp type was the traditional standard school fluorescent lamp of measured correlated colour temperature (CCT) 3600 K while the other lamp was of higher colour temperature with a measured CCT of 5500 K. The luminaires were specifically designed to provide equal luminance distributions for each lamp type.

Acuities were measured under three lighting conditions, either both lamp types providing equal task luminance or a condition where the task luminance of the 5500K lamp was set to a 50% lower value. The equal luminance conditions had the luminance at the eye of the

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tested student (in the direction of gaze) adjusted to the value 85 cd/m^2.

For the equal lighting condition, the Wilcoxon sign test applied to the results showed that visual acuity was significantly better ($P < 0.001$) under the higher CCT lamp with 24 of the 27 children having better acuity under the higher CCT lamp. There was one tie score while two scored better under the standard lamp. (Also noted, the tie student and one of reversals did better under the lower luminance condition than either of the other two conditions.)

Paired t-tests comparing the lower luminance condition showed a significant difference for the 5500 K lamps at the two luminances, but no significant difference when comparing the 3600 K lamps at the higher luminance value with the 5500 K lamps at the lower luminance. However there was a strong trend for the 5500 K lower luminance condition to provide better acuity with the results showing six ties and 14 out of the remaining 21 having better acuity under the lower luminance condition of the 5500 K lamps.

Pupil sizes of four children under the two different lamp types for the equal luminance condition were also measured based on averaging multiple frames of calibrated video camera images of their eyes. Average pupil size was significantly smaller under the 5500 K lighting as compared to the 3600 K lighting for all these children consistent with prior measurements of adults. This suggests an explanatory mechanism of the results based on the relatively more bluish spectral content of the 5500 K lighting causing comparatively greater pupil constriction and thereby improving visual optical quality. Based on visual acuity as a criterion for light level, these results imply a highly cost effective means for achieving improved vision and major energy savings by employing higher colour temperature lamps for school lighting.

2. Introduction and background

During the 1990s a number of laboratory studies carried out on young adults and set in simulated work environments compared the effects of different light spectra on visual acuity, contrast sensitivity and brightness perception.[1–4] Those studies found that light with greater blue content ie, higher correlated colour temperature (CCT) allowed better visual acuity and greater brightness perception compared to light of lower CCT, both lighting conditions controlled to be at the same photopic light level. Furthermore the laboratory studies demonstrated that the underlying mechanism for the acuity results was due to the greater effectiveness of bluish spectral content on pupil size variation. The higher CCT lighting yielded comparatively smaller pupils for a given photopic light level thereby confining the object light rays to the more central region of the eye where optical quality is generally better.

Subsequent studies on more than 100 young adults found similar results on both distance and near visual acuity where the spectrum of the surround lighting was varied while either the task lighting was the same as the surround or alternatively designed so that its spectrum remained fixed.[5,6] At the same illuminance level, surround lighting of higher CCT provided better acuity, consistent with the above laboratory results that claimed pupil size is mainly controlled by the surround lighting and its spectrum. It has also been speculated that the acuity benefits resulting from a spectrally driven smaller pupil would lead to an improvement in reading speed.[7] These previous studies suggest a new principle for lighting applications where higher CCT lighting is substituted for the present choice of lower CCT lighting that is the typical standard for most buildings. This principle allows, at one extreme, to obtain maximum acuity benefits by keeping light levels unchanged or at the other extreme to obtain maximum energy savings by lowering light levels with the higher CCT lighting while maintaining the status quo for acuity.

The extension of such a principle to school buildings would also be supported if the visual benefits obtained for adults occurred as well for children. The study reported here was undertaken principally for that reason.

3. Methods

3.1 Participating children

At the outset, letters were sent to the parents of fourth and fifth grade children of a local elementary school inquiring if they had any objections to their child volunteering for a vision test that used different kinds of classroom lighting. There were no objections and a large number volunteered to participate in the study. A subset of 27 children (12 girls, 15 boys) aged 10–11 from grades four and five were randomly chosen, with the amount limited by the available spare time of the testing optometrist. Five children wore spectacles and they used them during testing. The participating children were not aware of the purpose of the study and were told that they would be asked to read the smallest letters that they could see.

3.2 Luminaires, controls and lamps

Measurements were made in a windowless room of area 3m × 3.7m (10 ft × 12 ft) and height 3.4m (11 ft). Photos of the test room are shown in Figure 1. The ceiling was fitted with two equal four-lamp light fixtures. Each lighting fixture contained identical pairs of lamps: two GE-SP41F32T8SP4 and two Verilux-F32T8VLX lamps. The lamp intensities were adjustable via dimming ballasts controlled by a dimmer control box located on the room wall. The controls were designed so that either one pair or the other pair of the lamp types in both fixtures were powered together. The control box also contained an external switch allowing the experimenter to switch between the two lamp types. The luminaires were manufactured by 'MetalOptics' (subsidiary of Acuity Brands Lighting, Atlanta, Georgia) with specially designed optics, including placement of the lamps within each luminaire, so that each pair of lamps provided the same lighting distribution.

The nominal CCT values of the lamps as provided by the manufacturer were 4100 K and 6500 K respectively. However, because of the room furnishings and wall colourings, the measured CCT values on a horizontal surface at the desk level were 3620 K and 5500 K respectively (Minolta special photometer model xy-DC). The CCT values were also measured in the direction of gaze ie, the direction of view of the eyes of the tested student looking at the eye charts, and these had values of 2910 K and 4050 K, respectively.

3.3 Light levels

The illuminance at desk level from each lamp type was designed to be the same as in the regular classrooms where the horizontal illuminance at desk level was about 500 lux (50 fc). This was approximately achieved with the test room empty, but in the presence of the actual room furnishings the maximum achievable level was about 350 lux, a value nevertheless typical of elementary school lighting conditions. The test lighting condition for the comparison of the two-lamp types was first adjusted to achieve equal luminance in the direction of gaze of the student while seated at the desk and reading the eye charts. This assures that there will be an equal intensity of light in the viewing direction for the two lamp types. In this case the luminance was 85 cd/m^2, achieved with desktop horizontal illuminances of 350 lux for the high CCT lamp and 330 lux for the low CCT lamp. (A luminance of 85 cd/m^2 is typical for the screen of a good CRT monitor.) In addition, acuity testing was also carried out for the high CCT lamp with the light level adjusted to a 50% lower luminance (42.5 cd/m^2). Thus overall there were three

Figure 1 Various photos of the test room showing the desk, eye chart in place and in enlargement, the manikin head and video camera. Note that for both the pupil size measurements and related calibration the camera was moved from the position shown and placed on the table with the lens at the eye chart position

different lighting conditions: low CCT, high CCT and high CCT at 50%. Illuminance values were determined with a Minolta photometer model xy-DC and luminance values were determined with a Minolta luminance meter model CS-100 with an aperture set at 1° solid angle. Accuracy of the luminance meter within 3% was verified by absolute calibration with Photo Research Spectra Scan model #705 (spectra photometer).

3.4 Near visual acuity charts and scoring

Near visual acuity was measured using three standard Bailey–Lovie charts[8] reduced in size for a 400 mm viewing distance. The charts were printed with a HP ColorPro GA printer at 47.2 dots/mm (1200 dots/inch) that enabled good letter resolution down to a Snellen acuity level of 6/3 (20/10) (−0.3 logMAR). A standard measure of size used in general optometric practice is the logarithm of the minimum angle of resolution with the angle expressed in minutes of arc size. Thus an angle of 1 minute has logMAR = 0. The charts contained a logarithmic progression of 12 rows of five letters per row with each row 0.1 logMAR units smaller than the row above. The top row had a Snellen acuity of 6/38 (20/125) (0.8 logMAR) and continues to the bottom row of 6/3 (20/10) (−0.3 logMAR). Performance was scored by giving unit credit for each letter correctly identified beginning with a theoretical 6/600 (20/2000) line. As a result, a score of 95 was given for all letters correctly identified up to and including 6/7.5 (20/25) (0.1 logMAR), a score of 100 up to 6/6 (20/20) (0.0 logMAR) and a score of 105 for 6/4.8 (20/16) (−0.1 logMAR).

3.5 Testing

A practising licensed optometrist (MJM) measured the students' visual acuity with the charts held in a vertical position and at a testing distance of 400 mm. To maintain this distance during testing, a fixed string placed across the desk was in contact with the bridge of the student's nose. See Figure 1. A separate recording form was provided for each tested student that contained the particular chart letters and the lighting information. The following testing rules were then applied.

Each tested student was closely monitored to assure that the test distance was accurate and that s/he was not squinting. The student was firmly encouraged to guess all of the letters. Each measurement for all conditions was started on the top line and finished on the one line for which the student could not correctly identify any of the letters. They were tested on all lines in between. For each row on which the student was tested, each letter that they properly identified was circled on the recording form and added one point to the score.

3.6 Specific design

A Latin Square design was employed for testing so that the order of lighting conditions, acuity charts and combinations thereof were equalized across students. Thus any order effects were neutralized. This design led to three test sequences that are sequentially used throughout the study. These are:

Sequence 1: low CCT chart 1, 50% high CCT chart 2, high CCT chart 3, students 1, 4, 7, 10, etc
Sequence 2: 50% high CCT chart 3, high CCT chart 1, low CCT chart 2, students 2, 5, 8, 11, etc
Sequence 3: high CCT chart 2, low CCT chart 3, 50% high CCT chart 1 Students 3, 6,9,12, etc.

The recording form mentioned above identifies the order of the lighting conditions (low CCT, high CCT, high CCT at 50%) and the particular acuity chart (identified by the letters on the top line) to be used for each lighting condition. An adaptation time of 4 min under all of the lighting conditions was allowed before testing would commence during which time the optometrist engaged the students in conversations about various activities such as sports and vacations. The 4-min adaptation period was determined empirically during the course of obtaining pupil size measurements under the different spectra (see section 3.7 on pupil size measurements). Testing time was approximately 20 minutes for each student.

3.7 Pupil size measurements

In a separate testing session in the test room, pupil area measurements of four children (three girls, one boy) who did not participate in the acuity study but who were of the same age group were determined under the equal luminance condition for the low CCT and high CCT lightings. The measurements were obtained by analysing digital images of the portion of the upper face containing the eyes. The images were gathered by a Sony video camera (model 4000) at the rate of 28 frames per second with 10 s of data for each child under each lighting condition. Calibration of the images was determined by placing sensors of known fixed size in the eye position of a manikin's head placed in the student viewing position. During the data gathering the tested children fixated on the camera that was positioned on the desk at the chart position ie, 40 cm from their forehead. To assure that pupil size had adapted to the different lighting conditions, at least 5 min of adaptation time was allowed before data were taken. The pupil area was calculated from each frame by pixel count. Mean pupil area for each child under each lighting condition was determined by averaging the 70 data values obtained from every other frame over a 5-s data interval. The 5-s interval was arbitrarily chosen from the middle of the

10-s period but was the same selection for all the tested children. In addition to the mean pupil areas the maximum and minimum pupil areas of the continuously fluctuating pupil of each tested child were also determined.

4. Results

4.1 Near acuity scores

Table 1 lists the scores for each of the 27 tested children under the three lighting conditions based on the numerical algorithm described earlier.

The values in Table 1 show that for the equal luminance condition 24 out of 27 children had better acuity under the high CCT lighting compared with the low CCT lighting. This is highly statistically significant with a probability of less than 10^{-5} of a reversal by application of the Wilcoxon sign test. The mean visual acuity was approximately 2.5 letters better with the high CCT lighting (paired t-test, $P < 0.000005$). Comparison of the two high CCT lighting conditions shows that the 50% luminance condition had significantly lower visual acuity (paired t-test, $P = 0.002$) by approximately 1.5 letters. Thus this group of children was sensitive to a lowering of the light level. Visual acuity with the high CCT lighting at 50% luminance was approximately one letter better than the low CCT lighting at full luminance value but did not quite reach significance (paired t-test, $P = 0.056$) showing a strong trend for the 50% high CCT visual acuity to be better than the low CCT lighting at full value.

4.2 Pupil size

The results of the pupil area measurements for each of the four children tested are shown in Table 2 in units of mm^2. A paired t-test comparing the 70 datum for each child and for each of the equi-luminance lighting conditions showed there was a highly significant difference in mean pupil size for all four of the tested children with the high CCT condition providing a smaller pupil. The mean difference between the two conditions averaged over the four children was 2.18 mm^2. This magnitude of change in pupil area is larger than would be deduced from previous results of young adults for the lighting conditions of the test room.[1] This larger mean difference in pupil area for the children might not be expected because those previous young adults were measured with fixations greater than one meter but may be due in part to the claimed absence of

Table 1 Near Acuity score for each subject including overall means and standard errors. The lamps associated with high and low colour temperatures are denoted with the abbreviations HCCT and LCCT

Child	HCCT	LCCT	HCCT 50%	Child	HCCT	LCCT	HCCT 50%
student-1	104	102	104	student-15	100	95	95
student-2	106	104	103	student-16	102	103	105
student-3	103	101	104	student-17	105	96	104
student-4	102	100	96	student-18	105	104	105
student-5	105	103	103	student-19	97	94	94
student-6	109	106	105	student-20	105	104	109
student-7	104	100	98	student-21	105	101	105
student-8	105	99	102	student-22	107	104	105
student-9	106	100	103	student-23	101	101	103
student-10	104	104	104	student-24	107	104	106
student-11	104	103	102	student-25	105	99	103
student-12	106	105	103	student-26	108	105	106
student-13	107	108	105	student-27	107	105	105
student-14	106	105	105				
				Mean Value	104.63	102.04	103.03
				Std Error	0.5	0.65	0.67

Table 2 Average, min and max of measured pupil areas in mm^2 for each of the four children based on data obtained from 70 digital images per condition

H-CCT	11-Y-G	10-Y-G	11-Y-G	10-Y-B
Min	15.49	11.08	11.92	11.14
Max	19.41	15.92	15.40	14.10
Avg	17.71	13.03	13.72	12.64
L-CCT	11-Y-G	10-Y-G	11-Y-G	10-Y-B
Min	17.96	14.02	14.10	12.42
Max	23.28	16.92	16.96	14.58
Avg	20.64	15.89	15.53	13.75
H-CCT/L-CCT	11-Y-G	10-Y-G	11-Y-G	10-Y-B
Min	0.86	0.79	0.85	0.90
Max	0.83	0.94	0.91	0.97
Avg	0.86	0.82	0.88	0.92

Note: The column heading abbreviations eg, 11-Y-G indicates 11-year-old girl or boy etc.

accommodative pupillary reflex in young children.[9] Examination of the video pupil images of the four children showed that they were approximately circular in shape. To this extent, a mean difference in pupil diameter can be obtained from the data of Table 2 with the resultant value of 0.31 mm.

5. Discussion

The reading of printed matter or of a computer screen is one of the most ubiquitous activities of our society. A tried and true measure of the visual clarity of letters is the measurement of visual acuity, as better visual acuity means that the letters are seen more clearly and sharply.

A lighting environment that can provide optimum acuity in an economically efficient manner should therefore be considered as both desirable and advantageous.

The results of this study show that both light level and lighting spectrum affect visual acuity under typical conditions of reading. It is not surprising that light level affects acuity, but there is a general absence of appreciation for the effects of light spectrum. In this study where two different but commercially readily available light spectra were compared for their effects on the near visual acuity of elementary school children, the results showed significant effects of spectrum. At the same light intensity at the eye, visual acuity was significantly better for the high CCT lighting. Furthermore visual acuity was at least equal to (and with a strong trend to be better) than the traditionally installed low CCT lighting when the high CCT lighting level was reduced by 50% compared to the low CCT lighting. These results suggest a highly cost effective strategy for improving elementary school classroom lighting based on replacing the conventional low CCT (3500K) lamps with high CCT lamps (5500K or higher). The particular strategy varying at one end from maintaining the status quo in visual acuity with maximum savings in lighting energy costs or at the other end maintaining current lighting energy costs but providing a higher degree of visual acuity.

The changing of pupil size under the two different spectra offers a credible mechanism for the results obtained here. Such a mechanism is consistent with current views of optical quality of the eye[10,11] and with previous laboratory spectral acuity studies of both young and elderly adults.[1–4] These previous laboratory studies investigated the spectral and intensity variation of steady state pupil size of many adult subjects at typical photopic levels and established that pupil size variation closely followed a scotopic-like spectrum. The measured pupil size variations were completely incompatible with standard photopic sensitivity function. Similar conclusions about the spectral dependence of other pupillary behavior have recently been found in mice and primates.[12,13] A smaller pupil improves retinal image quality and visual acuity by eliminating peripheral aberrations and also by increasing the depth of focus for an eye especially with an uncorrected refractive error. At light levels typical of interior environments, this positive effect overcomes any reduction of acuity resulting from the decrease in retinal illuminance associated with a smaller pupil. This conclusion is also supported by data from previous studies.[1–4]

Each of the four children whose pupil size was measured under the two spectra had smaller pupils under the high CCT lighting. Although the pupil sizes of the participating children were not measured during the actual acuity testing, we suggest that if their pupils were measured, the resultant size differences would most likely be consistent with the data of the four children measured. Thus a parsimonious explanation of the spectral acuity effects found here is that these are a consequence of the spectrally induced pupil size changes.

The vertical placement of the eye chart during testing closely simulates the vision conditions of computer reading, especially the accommodation requirement. Because smaller pupils reduce the eyes' accommodative response[14] it is possible, besides the acuity benefit that a greater degree of visual comfort could be provided by high CCT ambient lighting in the computer environment.

6. Conclusions

The results presented here show that by changing from the more traditional 3500K lighting to higher colour temperature lighting it is possible to provide a higher quality of the visual environment at a reduced lighting energy cost. This double benefit should be a consideration for those concerned with management of elementary school education.

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Discussion

Comment on 'A Comparison of traditional and high colour temperature lighting on the near acuity of elementary school children' by S Berman, M Navvab, MJ Martin, J Sheedy, and W Tithof

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This paper is essentially an investigation of the effect of lamp spectrum and luminance on visual acuity. Therefore I am extremely disappointed to see that key previous research papers are omitted from their discussion, presumably because this previous work disagrees with the findings presented here. For example, Boyce *et al*[1] compared the performance of a Landolt ring task under two different fluorescent lamps (3000K and 6500K) at two illuminances (344 lux and 500 lux) and found that lamp spectrum had no effect on speed or accuracy of visual performance. Similarly, studies by Milova,[2] Halonen,[3] Halonen and Eloholma,[4] Vrabel *et al*.,[5] and Veitch and McColl[6] all found that lamp spectrum does not affect the performance of an achromatic visual task. So the first question is why did the authors choose not to mention that previous research in the area suggests that lamp spectrum will not affect visual acuity?

With higher luminances, a level of visual performance is reached which does not show significant change over a wide range of visual sizes contrasts and retinal illuminances: this is the plateau stage of the Relative Visual Performance Model. At some point either size, contrast or luminance will become insufficient and visual performance will rapidly collapse. Thus for most real applications, involving suprathreshold levels of luminance, task size and contrast, then differences in luminance would not yield a difference in visual acuity. At the luminances used in this study (85 cd/m^2 and 42.5 cd/m^2) it is expected that there would be no difference in visual performance for a suprathreshold task. That the authors do report a significant effect of luminance on task performance suggests that their task, identifying the smallest letter size that can be read, is one of threshold performance where even small changes in the lighting condition can yield a significant difference in visual performance. Therefore it must be questioned whether the current results have any validity for the intended application–I suspect not.

Of the three lighting conditions used in this study there are three comparisons to be made. The authors use two different statistical tests to compare differences of acuity under these three conditions; the effect of CCT using the Wilcoxon sign test, the effect of luminance using the paired *t*-test, and the final mixed comparison using the paired *t*-test. Will the authors please explain why they used two different tests; whether their conclusions would be maintained if they used the same test for all three conditions; whether they confirmed that the data are sufficiently normal to permit application of the *t*-test; and whether analysis of variance tests reveal an interaction between the three different conditions?

Table 1 presents three different measures of variance around the mean value. Will the authors please explain why it is necessary to present three such measures when one would suffice?

Finally, some further data are required to fully clarify this work:

1) Confirmation of the chart design—since not otherwise stated I have assumed it to be a high contrast black on white chart.
2) The lamps are not completely defined, only the CCT is given. Although the authors clearly identify the particular lamps used it would be helpful to identify the spectral power distribution and colour rendering index within the paper. Surprisingly, not even the S/P ratio is given.
3) Was the Optometrist paid for this work or is he a member of the research team, and did he have any previous knowledge of the relationship between lamp spectrum and visual acuity.

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Authors' response to SA Fotios

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The statement about not referencing studies that fail to agree with the results of the present paper is inaccurate. References 1, 2, 5 and 6 that Fotios refers to do not measure acuity (the smallest size discernable) as explained in written comments that accompany journal publications 1–4,9,10 and 11. For example in the Boyce *et al*. study the smallest size tested would be equivalent to testing only for the below average condition of 6/9 (20/30). In the study presented here there would not be any spectral effect if letters had been limited to 6/9 size. Thus the Boyce *et al*. study and our study are in agreement to the extent that they overlap, contrary to the comment of Fotios. The studies of references 3 and 4 (essentially the same) have not had the benefit of peer review in archival publications. In particular the studies of reference 4 suffer from methodological deficiencies.

Fotios and others have argued that the small size of letters that are employed to establish the spectral acuity effect are not present in 'real world' conditions and therefore the pupil size and spectral effect are irrelevant to lighting practice. This is *not* the case with the significance and relationship of acuity for 'real word' conditions having been established over a long period of time by the vision and optometric community. This is elaborated here.

The most extensive of this long history of work in vision relates acuity (the threshold condition) to general reading. One of the earliest works is that of Flom[1] who introduced the concept of 'visual acuity reserve'. (Flom determined that reading speed slowed as readers approached their threshold print size (letter acuity): ie, the deceleration in reading speed indicated that the limit of the readers 'reserve of resolving power' was approaching. Since the 1980s other vision researchers[2–6] have developed tests and conducted studies to determine the magnitude of the visual acuity reserve for normally sighted people of all ages.

Visual acuity reserve for individual readers is expressed as the ratio between the size of the smallest print that can be read *with best efficiency and comfort*, to the smallest size print that can be just barely correctly read (visual acuity).

The essence of this body of work is that reading speed will begin to slow down as letter size decreases. The slowdown starts to occur when the letter size reaches about 3–4 times the acuity limit and then begins an abrupt reduction in speed as letter size approaches the acuity limit. This size where the slowdown begins is referred to as the 'critical print size' The region of letter sizes larger than this critical size is referred to as the visual comfort zone and people like to be in their comfort zone.

For example, newspaper print is generally 8-point type and at normal reading distance this corresponds to 6/15 vision. A person needs to have just slightly better than 6/6 vision to be assured that they are in the visual comfort zone. However, newspapers are not printed with 3-point type although a person with 6/6 vision could read such type and thereby save much paper. The reason is because reading at that size would be slow and not in the comfort zone. The better the acuity a person has the more reserve that person has for remaining in the visual comfort zone with all visual tasks.

In particular Lueck *et al*.,[7] showed that normally sighted children of the age group studied here, needed four times their resolution reserve in order to reach maximum reading speed.

Thus a lighting spectrum that improves visual acuity will provide a larger comfort zone. Since there is much material 3–4 times threshold size in schools and workplaces, the assurance of at least 6/6 acuity *is* relevant to lighting practice.

In response to the statistical questions: for normality of the paired differences, the Shapiro and Wilk W test accepts all three differences but the Kolmogorov-Smirnov normality test rejects the high CCT versus low CCT condition difference at the 4% level, but accepts the other two (7.5% and >15%)[8]. The t-test was therefore not appropriate for comparing the low and high CCT at the same luminance, and therefore the non-parametric and very robust Wilcoxon sign test that does not require normality was thus applied showing the high degree of significance. (The t-test is appropriate for the other two tests). If the Wilcoxon sign test had been used in place of the t-tests for the other conditions the results would not have changed. The Wilcoxon test rejects equality of the acuities for the high CCT two light levels at the 0.13% level. It fails to reject equality of acuities for the Low CCT versus High CCT 50% condition at the 9.5% level.

Our study did not have a fully crossed design, with each factor being tested at each level of the other factor. Only three conditions were tested. This allows the determination of an overall mean, and two slopes. It does not allow the determination of an interaction term, as this would require one more condition.

Because each subject saw all three conditions the appropriate ANOVA for the experiment would be a two-factor ANOVA with subject and the lighting condition as the two factors. This ANOVA would be without replication (one data point per condition). Both subject and lighting condition are statistically significant at below the 0.001% level based on a Kruskal-Wallis non-parametric two-factor ANOVA. The ANOVA however, cannot be used to determine which conditions are different, and that is why the individual tests were reported.

Concerning Table 1, Fotios is correct in mentioning that providing three different measures of variance is excessive.

In response to the numbered points:

1) The charts were high contrast black on white as are all Bailey-Lovie charts.
2) The SPD in the direction of gaze would be quite different from the individual lamp primary SPD because of room reflectivities (reflected by the differences in measured CCT values). Unfortunately it is not possible to return to the school to measure the full SPD in the direction of gaze.
3) All authors were pro bono. Before the study began the testing optometrist (MJM) did not have previous knowledge about lamp spectrum and acuity but he was aware of the testing hypothesis.

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