
Volume 29
Issue 1
March 2009
ISSN 0272-4944
ELSEVIER
Journal of
ENVIRONMENTAL
PSYCHOLOGY
Published with the Support of the Division of Environmental Psychology of the International Association of Applied Psychology and the International Association for People-Environment Studies

Journal of Environmental Psychology 29 (2009) 63–75

Contents lists available at ScienceDirect

Journal of Environmental Psychology

journal homepage: www.elsevier.com/locate/jep

Lighting and discomfort in the classroom

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ARTICLE INFO

Article history:
Available online 11 December 2008

Keywords:
Coloured overlay
Discomfort
Disability
Fluorescent lighting
Glare
Interactive whiteboard

ABSTRACT

Aspects of classroom lighting and décor that can promote discomfort and impair task performance through glare, and imperceptible 100 Hz flicker from fluorescent lighting, were examined in a sample of UK schools. In 90 classrooms, across eleven secondary schools and six local education authorities variables measured included flicker, illuminance at desks, and luminance of whiteboards. Results showed that 80% of classrooms are lit with 100 Hz fluorescent lighting that can cause headaches and impair visual performance. Mean illuminance (from excessive day- and artificial lighting) was in excess of recommended design illuminance in 88% of classrooms, and in 84% exceeded levels beyond which visual comfort decreases. Lighting could not be adequately controlled due to classroom design and infrastructure. Ceiling-mounted data-projectors directed at whiteboards mounted vertically on the wall resulted in specular reflection from the whiteboard, visible as a glare spot with luminance high enough to cause discomfort and disability glare. The intensity of the glare spot varied between different brands of whiteboard. Ambient lighting, needed for close work at pupils' desks, reduced image contrast. Venetian blinds in 23% of classrooms had spatial characteristics appropriate for inducing pattern glare. There was significant variation between schools and local authorities. These findings may provide insights into small-scale reports linking pupils' attainment, behaviour and learning to classroom lighting, and may also help explain some of the benefits of coloured overlays for pupils' reading.

1. Introduction

There is evidence that classroom lighting may be important for pupils' learning. Teachers and pupils can have clear preferences about classroom lighting (Schneider, 2003); for example, Hathaway (1983) found that teachers had preferences for daylight, whilst Lang (2002) indicated that teachers liked to have *control* over lighting levels. Small-scale studies have also proposed a link between lighting and attainment. For example, Hathaway (1994) found links between use of full spectrum fluorescent lamps and attainment. Using a large sample, Heschong and Knecht (2002) found significant correlations between attainment and both (1) the extent to which daylight could be controlled by the teacher, and (2) the extent to which daylight was diffuse throughout the classroom. A number of studies have also noted changes in behaviour under particular lighting regimes. Fenton and Penney (1985) found that autistic children engaged in more repetitive behaviours under fluorescent light; Schreiber (1996) suggested that children became more relaxed and interested in classroom activities when brightness was reduced; Shapiro, Roth, and Marcus (2001) found that children's maladaptive behaviour became less frequent under indirect diffuse full spectrum fluorescent lamps; whilst Treichel (1974) suggested that fluorescent lighting may aggravate hyperactivity in school children. Finally, other authors have concerned themselves with the effect of environmental variables such as lighting on the learning process itself. Dyck (2002) suggested that aspects of lighting are necessary to establish a state of "flow" (Csíkszentmihályi, 1990); Lyons (2002) suggested that full spectrum fluorescent lighting can benefit learning; Rittner and Robbin (2002) indicated that daylight helps students to retain and learn information; whilst Schulz (1977) examined the importance of avoiding excessive illumination. Some authors place most emphasis on the importance of daylighting, but the need for integrated systems of day- and artificial lighting is broadly accepted (see Woolner, Hall, Higgins, McCaughey, & Wall, 2007).

The manner in which the above studies were conducted is very variable, with some being based on very small sample sizes, limiting generalisation. Although recommendations for best practice do exist (CIBSE, 2004; DfEE, 1999), classroom lighting has continued to change (including for example, developments in fluorescent lighting and introduction of data-projectors to

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doi:10.1016/j.jenvp.2008.11.007

classrooms), whilst research in the field has been neglected by comparison (Woolner et al., 2007).

Establishing causative links between aspects of classroom environment and the factors mentioned above is difficult, in part because of the practical and ethical difficulties in conducting controlled trials in classrooms. Hence, this study takes a different approach; that is, to assess the extent to which pupils in UK classrooms are exposed to some of the aspects of classroom lighting and décor which have been shown to cause discomfort and impair task performance, and which may therefore begin to inform the debates above. These aspects are imperceptible 100 Hz flicker from fluorescent lighting, and glare induced by (1) daylight and fluorescent lighting, (2) interactive whiteboards (IWBs) and dry-wipe whiteboards (DWBs), and (3) patterns from Venetian blinds.

1.1. Imperceptible 100 Hz flicker in light from fluorescent lamps

Electric lamps that operate on an AC supply (50 Hz in Europe) have inherent modulation in light output at twice the supply frequency (100 Hz in Europe) (CIBSE, 2004). Conventional incandescent lamps show a small modulation because the filament takes time to cool between cycles, whereas fluorescent discharge lamps show a modulation in illuminance (peak-trough) between 17% and 100% (CIBSE, 2004) one hundred times per second (100 Hz).

100 Hz modulation can adversely affect visual search performance (see Jaen, Sandoval, Colombo, & Troscianko, 2005), even though subjects do not consciously experience it as flicker (Berman, Greenhouse, Bailey, Clear, & Raasch, 1991). Subjects who report adverse effects from fluorescent lights show higher sensitivity to 100 Hz flicker (Dakin, Hargroves, Ruddock, & Simons, 1994), and indeed to visible flicker at lower frequencies (Brundrett, 1974). Fluorescent lamps are housed in lighting fixtures, or luminaires, within which is control circuitry that operates the lamps, determining the rate of flicker. Increasing the frequency of flicker into the kHz range, using the same lamps but driving them with high frequency control circuitry, can reduce headaches under double-masked conditions (Wilkins, Nimmo-Smith, Slater, & Bedocs, 1989) and enhance task performance; individuals read more accurately (though more slowly) than under 100 Hz flicker (Küller & Laike, 1998) and display improved visual search performance (Jaen & Kirschbaum, 2001; Jaen et al., 2005). Interestingly, Lindner and Kropf (1993) found younger individuals demonstrated relatively high sensitivity to 100 Hz flicker. The choice of fluorescent circuitry for school classrooms could therefore be very significant, and may adversely affect pupils' task performance and learning.

Neurophysiological responses suggest mechanisms for the effect of flicker on performance. Berman et al. (1991) demonstrated electroretinogram responses to 100 Hz flicker. Küller and Laike (1998) reported attenuation of EEG alpha waves. In cats, neurons in the lateral geniculate nucleus (LGN: a subcortical structure in the visual system) show phase-locked firing in response to 100 Hz flicker, suggesting timing of neural responses in subcortical structures connected to the LGN may be disrupted (Eysel & Burandt, 1984). These structures include the superior colliculus, which is responsible for eye movements. It is already known that control of human eye movements can be affected by flicker; Baccino, Jaschinski, and Bussolon (1999) found changes in saccade velocity and extent in response to flickering CRT monitors, whilst Wilkins (see Wilkins, 1986; Wilkins et al., 1989) found enlarged saccadic movements in response to flicker from fluorescent lights.

1.2. Disability and discomfort glare

Glare happens when one part of the visual scene is much brighter than the general brightness of the rest of the field of view. A high source luminance, large source area, low background luminance and a position close to the line of sight all increase glare. Such glare can be of two types: disability glare and discomfort glare.

Disability glare refers to a decrease in visual performance, which results from a decrease in contrast due to light scattered within the eye. Scatter is greatest when a bright light source is close to the direction of gaze. The light is scattered mainly by the lens of the eye, but also by the cornea, reducing the contrast of the retinal image. Even without reduction in visual performance, glare may also result in discomfort (discomfort glare), with symptoms including eyestrain and headaches. Effects may be immediate, or recognised only after prolonged exposure.

1.2.1. Illuminance at pupils' desks

CIBSE (2004) provide recommended design illuminances for different types of classroom, which range from 300 lux to 500 lux; adoption of such values helps to restrict glare to reasonable levels (it is worth noting that a new installation with new lamps and clean surfaces may give an illuminance 25% greater than the design illuminance, but only half this initial value when lamps are old and dirt has accumulated). There is some evidence for increased discomfort at illuminance above 1000 lux and separate evidence above 2500 lux (Rea, 1982, 1983; Smith & Rea, 1980) in uniformly lit rooms. The data reported in this paper are analysed against these values, but do not take into account uniformity ratios across task area and classroom. However, in rooms that are not uniformly lit, with the immediate task area much brighter than the surrounding area, discomfort effects may be exaggerated.

1.2.2. Luminance and glare from data-projection screens

By 2004, data-projectors and IWBs had been installed in 92% of English secondary schools (see DfES, 2004). Some reports suggest that children can find data-projected images difficult to see (Hall & Higgins, 2005; Smith, Higgins, Wall, & Miller, 2005). Difficulties may arise from ambient light (daylight and fluorescent light) reflecting off the whiteboard; as well as glare from direct reflectance of the projector beam itself. Conventional slide projector screens have a matt surface that reflects incident light in every direction so the image can be seen from any viewing angle. More glossy surfaces do not scatter light so well: they reflect some of the light at an angle equivalent to the angle of incidence in the same way as a mirror (specular reflection). If a data-projector shines from the ceiling at a vertical surface such as a whiteboard, specular reflection is directly visible to the audience, appearing as a bright 'glare spot' on the board (see Fig. 1), which may cause disability and

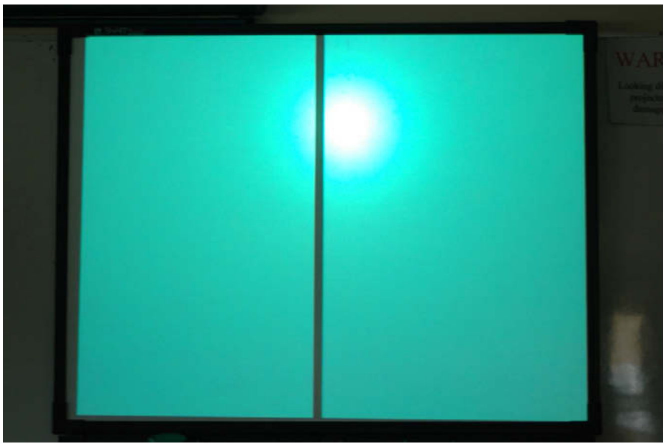

Fig. 1. Interactive whiteboard (Brand 2) with projected vertical stripe. The glare spot is clearly visible.

discomfort glare. Rather than install relatively costly IWBs, some schools opt to project onto DWBs. These have a glossy surface and may generally give more glare.

1.2.3. Pattern glare from window blinds

Striped patterns can be responsible for visual stress (Wilkins, 1995), and provoke headaches, migraines (Harle, Shepherd, & Evans, 2006) and epileptic seizures (Fisher, Harding, Erba, Barkley, & Wilkins, 2005; Wilkins, 1980). Glare from striped patterns depends on the spatial frequency of the pattern, its duty cycle (ratio of dark to light stripes), its size (subtense at the eye), and contrast (see Wilkins, 1995, p. 40). Striped patterns produced by shadowing of Venetian blinds can have a spatial frequency within the range appropriate for the induction of visual stress. The extent to which Venetian blinds of appropriate dimensions are installed in classrooms will determine the extent of pattern glare to which pupils are subjected.

2. Method

To establish the extent to which pupils are exposed to inappropriate sources of flicker and glare, lighting was sampled in 90 classrooms across eleven secondary schools, randomly selected from the partner schools of the Faculty of Education, University of Cambridge. Two schools were selected from each authority (with one exception, where only one school was available). In three cases where schools declined to be involved, a new school was randomly selected from the remainder. Within each school, sampling of classrooms was random, but stratified across buildings, such that the number of classrooms sampled in each building was in proportion to the number of 'curriculum areas' housed within that building. This approach was intended to ensure that the sample was representative of pupils' experience throughout the school. Data collection took place during the UK summer holidays, between 24th July 2006 and 4th September 2006, when daylight levels may have been higher than average. In each classroom, a sketch plan was made of the position of the IWB or DWB, pupils' desks, luminaires and the number of lamps housed within each. Dimensions of floor area, as well as positions, and dimensions of windows, were also marked on the plan. A summary of such data is provided in Appendix 1.

2.1. Imperceptible 100 Hz flicker in light from fluorescent lamps

Imperceptible 100 Hz flicker from fluorescent lamps was assessed by viewing them through the aperture of a servo-controlled rotating shutter set to 104 occlusions per second (Princeton Applied Research Model 197). Any 100 Hz flicker was visible through the aperture as a 4 Hz beat, and marked against the relevant luminaire on the classroom plan. These data were used to calculate the percentage of 100 Hz and high frequency luminaires in each classroom, and the percentage of classrooms lit solely by 100 Hz luminaires. Where visible on the lamp surface, technical specifications of each lamp, including colour temperature, were also recorded.

2.2. Illuminance at pupils' desks

Illuminance was assessed using a lux meter (RS Components Ltd 610-815), positioned horizontally on the surface of either four, five or six pupils' desks (as appropriate to the arrangement of pupils' desks in the room), chosen to enable representative sampling across the room (see Fig. 2) (in this paper uniformity ratios across task areas on pupils' desks or across the classroom are not examined). At each point, levels were assessed under four lighting conditions: (a) lights on, blinds open, (b) lights off, blinds open, (c) lights on, blinds closed, and (d) lights off, blinds closed. Note was also made of the extent to which teachers could control illuminance by recording on the classroom plan (a) the position of light switches, (b) an indication of which switch controlled which luminaire, (c) the presence or absence of blinds or curtains on each window, and (d) whether each curtain or blind was functioning properly. Prior to such measurements, a record was made of percentage cloud cover, and whether the sun was visible.

2.3. Luminance and glare from data-projection screens

A standard image (single central black stripe on a white background) was projected against the whiteboard (see Fig. 1). The width of the stripe approximated the same number of black pixels as occupied by a slide of text, so the overall luminance of the image was representative of that used in class. Luminance levels were

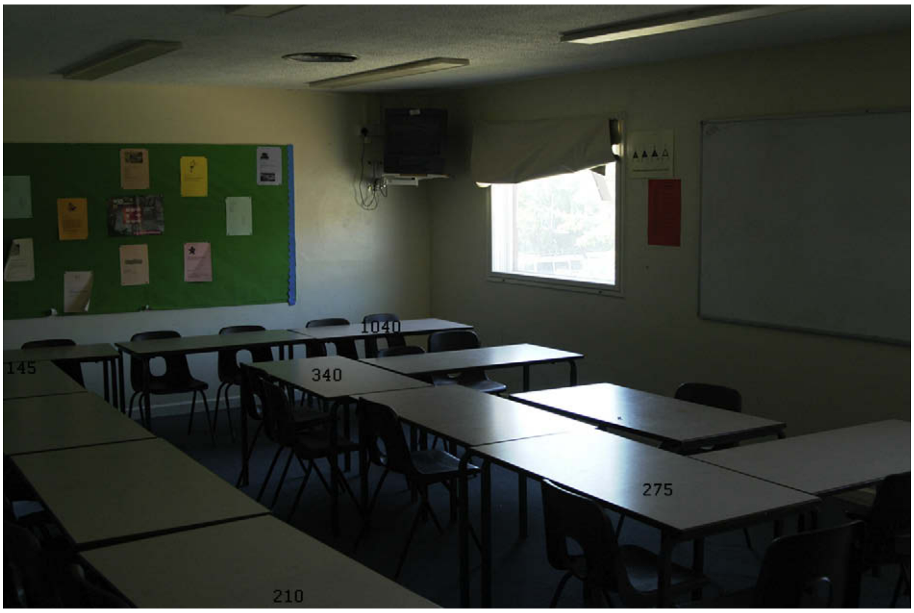

Fig. 2. Photograph of a classroom with measurements of illuminance indicated (lux) (the values shown were obtained with blinds fully open and fluorescent lights off).

assessed using a Minolta (LS-110) spot photometer under four conditions: (a) lights on, blinds open, (b) lights off, blinds open (c) lights on, blinds closed, and (d) lights off, blinds closed. Luminance was measured (1) outside the glare spot and (2) within the glare spot (i.e. where light from the projector was reflected directly towards the photometer). In both cases, two sets of readings were taken by adjusting the viewing position so the glare spot was situated across the black stripe and outside the black stripe (see Fig. 1). For all such measurements, Michelson contrast ($L_{max} - L_{min}$/$L_{max} + L_{min}$; L_{max} = luminance from white background; L_{min} = luminance from black stripe) was calculated.

Luminance of two portable IWBs in controlled conditions was also assessed, enabling examination of each brand's surface properties. Reflectance was measured using the Monolite system according to CIE (International Lighting Commission) standards. An estimate of the ratio between specular and diffuse components of reflection was obtained by comparing reflectance in a 45–90° configuration with that at 45–45°. A second estimate was obtained by taking luminance readings as described above, but by projecting a grating with square wave luminance profile, with cycle width 0.1 m and maximum contrast. For each brand, the Michelson contrast was calculated, outside and inside the glare spot.

2.4. Pattern glare from window blinds

The type and number of blinds in each classroom were recorded. Blinds were photographed, and for a number of typical classrooms, the spatial frequency of striped patterns produced by shadowing of Venetian blinds (see Fig. 3) was estimated, and compared to the range appropriate for inducing visual stress (1–10 cycles per degree).

2.5. Analysis

Data were analysed using descriptive and non-parametric statistics. Given the exploratory nature of this paper, analyses treat classrooms as independent data points. Where appropriate, differences between schools and local authorities are outlined. Means are given ± standard error.

3. Results

3.1. Imperceptible 100 Hz flicker in light from fluorescent lamps

20% of classrooms were lit solely by high frequency fluorescent luminaires. In the remaining 80% of classrooms, a mean of 90% of luminaires exhibited 100 Hz flicker (Fig. 4). Judging from the lamp markings, lamps with a colour temperature of 3500 K were twice as common as those with lower colour temperature. The depth of modulation of these lamps is sufficient to cause headaches (Wilkins et al., 1989).

3.2. Illuminance at pupils' desks

Mean illuminance (Table 1) ranged from inadequate (38 lux) to excessive (in excess of 2500 lux – the upper limit of the meter). When lit with all available daylight and artificial lighting (blinds open, lights on), mean illuminance at pupils' desks was 1168 ± 55 lux (Fig. 5). Mean illuminance was lower with blinds open and lights off (807 ± 60 lux) (Fig. 6), and with blinds closed and lights on (684 ± 51 lux) (Fig. 7), but still in excess of recommended design illuminances for school classrooms (which range from 300–500 lux depending on the type of classroom) (CIBSE, 2004). Indeed, mean illuminance was more than 25% in excess of 500 lux (see Section 1.2.1). Illuminance was in excess of 1000 lux, the point at which visual comfort can start to decrease (Rea, 1982, 1983; Smith & Rea, 1980), in at least one area of the classroom, in 84% of classrooms with lights on and blinds open, and in 39% of classrooms with lights on and blinds closed. In many cases (see Table 1), high illuminance levels in one area of the classroom were accompanied by much lower levels in another area, which itself can contribute to enhanced visual discomfort and/or reduced task performance (Slater, Perry, & Carter, 1993).

Excessive illuminance was caused by (1) daylight and (2) fluorescent lighting, with the former most influential (see Table 1):

(1) In rooms with functioning blinds, mean illuminance with lights off and blinds open (846 ± 80 lux) was significantly higher than illuminance with lights on and blinds closed (710 ± 71 lux)

Fig. 3. Venetian blinds.

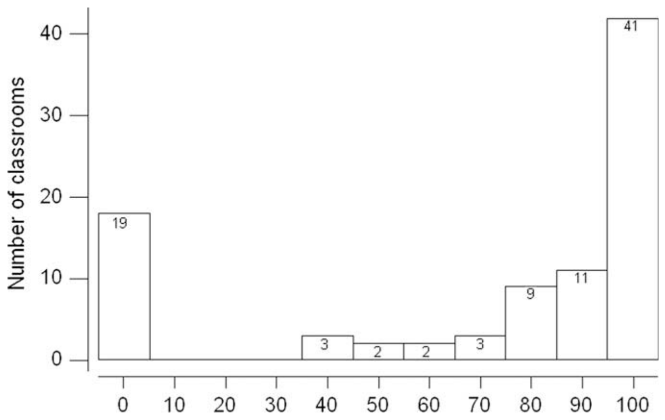

Fig. 4. Percentage of luminaires with 100 Hz flicker.

($T = 585.0$, $N = 35$, $p < 0.001$), suggesting that daylight can contribute more than artificial lighting to net illuminance. There was no significant relationship between the number of fluorescent luminaires and illuminance with lights on and blinds open ($r = 0.081$, $p = 0.447$), although this relationship was significant (but relatively weak) when the blinds were closed ($r = 0.291$, $p = 0.005$), again suggesting that daylight can contribute more to illuminance than fluorescent lighting. Mean illuminance with lights off and blinds open was also weakly but significantly related to the total window area ($r = 0.352$, $p = 0.001$), the source of incident daylight. However, it should be noted that mean illuminance at pupils' desks was not significantly related to the percentage cloud cover ($r = -0.132$, $p = 0.216$) or whether the sun was visible ($t_{(89)} = 1.75$, $P = 0.084$) (when measured outside the teaching block immediately before classroom data collection).

(2) In 64% of classrooms, minimum recorded illuminance was above 300 lux with lights on and blinds closed (Table 1). Even when classrooms with broken or missing blinds were excluded, the figure was still 60% (Table 1), suggesting deliberate over-lighting with artificial light.

Teachers' ability to control (1) daylight and (2) fluorescent lighting was compromised by classroom design, malfunction and maintenance:

(1) There was no correlation between floor area and total window area ($r = 0.103$, $p = 0.340$), suggesting inconsistent attitudes to daylighting in building design. Blinds were absent in 23% of classrooms. In 51% of those that had blinds, the blinds were either broken, or at least one was missing. Mean illuminance was in excess of 300 lux in 81% of classrooms with lights off and blinds open (Table 1), but with blinds closed, it was still in excess of 300 lux in 24% of classrooms, suggesting that blinds were often ineffective in controlling daylight. A mean of 1.4 ± 0.2 blinds per classroom were absent or malfunctioning, affecting a mean of 39% of window area per classroom.

(2) There was a strong significant correlation between floor area and the total number of luminaires ($r = 0.727$, $p < 0.001$), suggesting some attempt to provide at least minimum illuminance in poorly daylit areas of the classroom. However, this tended to produce excessive illuminance in areas that were well daylit, as evidenced by the maximum illuminance values (with blinds open and lights on) in Table 1. The number of luminaires was not related to total window area (the source of incident daylight) ($r = 0.055$, $p = 0.604$). Compensation for excessive daylight, by selectively switching off luminaires close to windows, was impossible in 27% of classrooms. The extent to which it was possible in the remainder was variable; the number of luminaires per switch ranged from 2 to 12. Only two classrooms had luminaires that automatically dimmed in response to daylighting; none was dimmable by teachers.

(3) A mean of 5% of fluorescent lamps per classroom had not been replaced after malfunction.

3.3. Luminance and glare from data-projection screens

With one exception, whiteboards were mounted vertically on a wall with their projector on the ceiling (see Fig. 9). Hence, specular reflection of the projector lamp was directed into pupils' eyes, creating a glare spot on the screen (see Fig. 1). The presence of a visible sheen (see Fig. 10) on the screen indicated the extent of such glare.

(1) The luminance of the glare spot was measured under all lighting conditions (Table 2). When measured with lights on and blinds open, the maximum measured luminance (324,000 cd m^{-2}; measured on a DWB) approached dangerous levels. The mean luminance of DWBs ($56{,}635 \pm 20{,}014$ cd m^{-2}) was about 50 times that from IWBs (1032 ± 151 cd m^{-2}) ($H_{(1)} = 30.6$, $p < 0.001$) and was in excess of 100,000 cd m^{-2} on 19% of boards.

(2) Luminance of the glare spot differed between brands of IWB (Table 2). Brands 1 and 2 were the two most prevalent brands observed in this study, and are widely recognised as the 'market leaders'. With lights on and blinds open, the mean luminance of the glare spot for Brand 1 was 376 ± 42 cd m^{-2}, whilst for Brand 2 it was 1850 ± 220 cd m^{-2}. The remaining brands of IWB had values between these extremes.

(3) Measured under laboratory conditions, the ratio of specular (mirror-like) to diffuse reflection for Brand 1 was 1.3, whilst the ratio for Brand 2 was 3.7, confirming a higher proportion of specular reflection in Brand 2, and explaining the higher luminance of the glare spot. Within the glare spot, contrast was reduced from 0.93 to 0.91 for Brand 1, and 0.92 to 0.53 for Brand 2, confirming that disability glare exists, and that its extent varies in proportion to the extent of specular reflection.

(4) Contrast on Brand 1 was less affected by the glare spot because the surface of the board had less sheen. The quality of the sheen could be assessed very simply by holding a fingernail against the board. No reflection of the fingernail was visible on Brand 1, but a reflection could be seen on all the other IWBs (63% of total) and also, particularly clearly, on the DWBs. The sheen, assessed in this way, was useful in predicting differences in mean luminance from the glare spot: 1440 ± 200 cd m^{-2} for IWBs with a visible reflection and 376 ± 42 cd m^{-2} for those without ($H_{(1)} = 18.54$, $p < 0.001$) (Table 2). When measured with lights on and blinds open, glare spot luminance was in excess of 1000 cd m^{-2} in 52% of IWBs with a visible reflective sheen, and in none of those without. The presence or absence of a visible reflective sheen therefore provides an indication of the ratio of specular to diffuse reflection, the luminance of the glare spot and the likelihood of disability and discomfort glare.

When compared to the recommended luminance of paper (70 cd m^{-2}), luminance of IWBs and DWBs was high, and differed between the two types, and also between brands of IWBs. When the luminance was measured away from the glare spot, there were significant differences between different lighting conditions with respect to mean luminance and contrast (Table 3); mean contrast was highest under minimal ambient lighting (blinds closed, lights off) and lowest under full lighting (blinds open, lights on).

Table 1
Mean, highest (max) and lowest (min) classroom illuminance (lux) measured under different lighting conditions. Each row represents one classroom.

Local education authority	School	Sun visible	Cloud cover (%)	At least one blind absent or malfunctioning	Illuminance with lights off–blinds closed (lux)			Illuminance with lights on–blinds open (lux)			Illuminance with lights off–blinds open (lux)			Illuminance with lights on–blinds closed (lux)		
					Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
1	1	Yes	5	Yes				1650.0	2100	1200	184.0	360	45	1650.0	2100	1200
1	1	Yes	5	No				1160.8	2500	360	857.5	2400	55	359.2	420	230
1	1	Yes	5	No				1063.3	2500	320	837.5	2500	130	283.3	430	170
1	1	Yes	5	Yes				1016.7	1150	750	561.7	850	365	1016.7	1150	750
1	1	Yes	5	Yes				803.0	1800	230	516.0	1550	90	291.0	500	110
1	1	Yes	5	Yes				784.2	1250	420	485.0	1040	145	127.6	195	38
1	1	Yes	5	Yes				424.2	575	315	152.5	320	45	326.7	375	295
1	1	Yes	5	Yes				306.1	455	145	306.1	455	145	306.1	455	145
2	2	Yes	40	No				2500.0	2500	2500	2500.0	2500	2500	1833.3	2250	1450
2	2	Yes	30	Yes				2500.0	2500	2500	2125.0	2500	1750	2500.0	2500	2500
2	2	Yes	30	Yes				2330.0	2500	1800	2220.0	2500	1500	2330.0	2500	1800
2	2	Yes	10	No				2130.0	2500	1600	2005.0	2500	1850	940.0	1400	600
2	2	Yes	5	Yes				1796.4	2500	1175	1650.0	2500	1000	1796.4	2500	1175
2	2	Yes	10	No				1625.0	2500	750	1446.7	2500	330	1448.3	2150	440
2	2	Yes	5	No				1537.5	2500	650	1306.7	2500	400	695.0	1350	300
2	2	Yes	10	No				1446.7	2500	480	1130.8	2500	220	438.3	550	315
2	2	Yes	5	No				1166.7	2150	550	766.7	1700	265	508.3	600	400
2	2	Yes	20	Yes				719.20	1075	455	504.2	875	210	719.2	1075	455
2	8	No	100	Yes	1683.3	2500	1275	2200.0	2500	1550	2125.0	2500	1400	1870.8	2500	1350
2	8	Yes	70	Yes	1171.3	1850	320	1709.4	2425	750	1171.3	1850	320	1709.4	2425	750
2	8	No	100	Yes	406.0	1500	370	1498.3	2500	390	1149.2	2500	160	790.8	1500	370
2	8	No	100	Yes	775.0	2050	120	1131.3	2350	600	858.8	2050	385	940.0	2375	270
2	8	Yes	75	Yes	31.4	42	16	955.0	1350	625	496.0	975	150	556.0	600	430
2	8	No	90	Yes	38.7	135	10	576.0	1000	270	474.0	1100	105	249.0	355	195
2	8	No	90	No	2.4	6	0	332.5	460	170	191.9	470	50	142.5	170	95
3	3	Yes	95	Yes				1966.7	2500	1450	1675.0	2500	950	603.3	850	460
3	3	Yes	20	Yes	0.4	1	0	1404.0	2500	370	1265.0	2500	240	149.0	230	80
3	3	Yes	5	Yes				1375.0	2500	700	1120.0	2500	405	1375.0	2500	700
3	3	Yes	5	Yes				1354.2	2500	525	905.0	2200	100	1354.2	2500	525
3	3	Yes	50	No				1310.0	2200	550	936.0	1850	230	341.0	390	315
3	3	Yes	50	Yes				1150.0	1500	750	995.0	1250	650	1150.0	1500	750
3	3	No	100	Yes				1042.5	2500	455	714.2	2400	160	554.2	900	380
3	3	No	80	Yes				805.0	1100	600	124.8	315	18	805.0	1100	600
3	3	Yes	20	Yes				375.8	485	280	85.0	165	25	375.8	485	280
3	5	No	60	No	8.3	16	3	1754.2	2500	750	1310.0	2500	270	450.8	475	380
3	5	No	100	No	21.6	46	8	1368.0	2500	390	777.0	2100	95	456.0	575	280
3	5	No	100	No	33.8	55	20	1191.7	1575	700	609.2	1100	225	571.7	700	460
3	5	No	60	No	8.4	20	3	1046.0	2000	480	598.5	1550	130	483.0	575	380
3	5	No	95	No	7.3	10	6	945.0	1300	700	618.0	875	390	320.0	370	250
3	5	No	60	No	0	0	0	571.0	850	410	108.8	227	29	455.0	650	345
4	4	Yes	50	Yes	420.0	1900	60	1391.7	2500	700	996.7	2500	280	803.3	2400	410
4	4	Yes	80	Yes	381.7	900	100	1360.0	2500	460	945.0	2200	215	755.0	1350	440
4	4	Yes	0	No	95.4	220	45	1270.8	2500	625	907.5	2300	230	456.7	575	390
4	4	Yes	15	No	13.6	39	3	1079.2	2500	500	641.7	1900	200	386.7	420	340
4	4	Yes	25	Yes	371.0	2000	22	938.3	2500	170	816.7	2500	65	535.0	2200	140
4	4	Yes	50	No				810.0	1100	600	477.5	850	65	810.0	1100	600
4	4	Yes	0	No	1.7	10	0	718.3	1900	390	350.0	1300	60	302.5	370	250
4	4	Yes	50	No				568.1	900	385	259.5	800	95	568.1	900	385
4	6	No	100	Yes	135.8	600	14	1833.3	2500	1050	1481.7	2400	500	551.7	800	400
4	6	No	100	No	58.4	105	18	1360.0	2100	700	877.0	1700	170	603.0	750	340
4	6	No	100	No	5.3	10	3	1079.2	1900	600	616.7	1450	125	461.7	650	380
4	6	No	100	No	34.6	60	8.5	857.5	1250	470	787.5	1150	305	236.0	250	210
4	6	No	100	Yes	296	600	100	835.0	1050	625	296.0	600	100	835.0	1050	625
4	6	No	100	Yes	279.2	440	140	820.8	1050	650	279.2	440	140	820.8	1050	650
4	6	No	100	No	125.3	350	29	773.3	1400	310	468.3	1200	105	331.7	600	230
4	6	No	100	Yes	0.3	2	0	679.2	1000	250	233.3	600	40	397.2	500	215
4	6	No	100	Yes	163.0	340	50	490.0	700	270	163.0	340	50	490.0	700	270
4	6	No	100	Yes	0.8	4	0	464.2	925	335	305.0	750	95	151.7	165	135
5	7	No	100	No	71.7	105	50	1770.8	1925	1625	1233.3	1550	1075	440.0	525	390
5	7	Yes	60	Yes	343.0	700	100	1505.0	2500	850	1240.0	2500	550	520.0	800	210
5	7	No	100	Yes	614.2	1200	210	1212.5	2050	750	811.7	1700	270	1000.0	1500	550
5	7	No	100	Yes	3.1	7	0	1085.0	2200	550	528.6	1700	32	509.0	700	415
5	7	No	100	Yes	101.4	340	0	1045.0	2275	150	859.0	2150	65	319.5	525	92
5	7	No	100	No	5.4	9.5	3	820.0	1400	345	497.5	900	47	288.3	350	170
5	7	No	100	Yes	399.4	750	100	725.0	1100	320	399.4	750	100	725.0	1100	320
5	7	Yes	50	Yes	457.5	1250	83	673.0	1475	250	457.5	1250	82	673.0	1475	250
5	7	Yes	60	Yes	50.0	110	9	356.0	430	240	50.0	110	9	356.0	430	240
5	7	No	100	Yes	4.4	17	0	332.0	410	290	38.7	67	18	330.0	395	270
5	10	Yes	35	No	38.4	70	23	2238.9	2500	1800	2075.0	2500	1450	314.4	410	240
5	10	Yes	25	No	145.8	350	65	2229.2	2500	1250	2075.0	2500	1000	392.5	575	300
5	10	No	90	No	25.8	41	18	1925.0	2500	875	1800.0	2500	900	183.3	275	80

Table 1 (*continued*)

Local education authority	School	Sun visible	Cloud cover (%)	At least one blind absent or malfunctioning	Illuminance with lights off–blinds closed (lux)			Illuminance with lights on–blinds open (lux)			Illuminance with lights off–blinds open (lux)			Illuminance with lights on–blinds closed (lux)		
					Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
5	10	Yes	60	Yes	8.5	22	3	603.3	1100	380	182.0	460	42	365.8	470	300
5	10	No	90	Yes	15.3	70	3	400.0	700	270	165.3	420	42	317.5	390	255
6	9	No	100	No	62.8	140	24	1579.2	2500	750	1348.3	2500	350	388.3	475	270
6	9	No	100	Yes	102.8	305	23	1491.7	2500	750	905.0	2000	195	670.8	825	600
6	9	No	100	No	19.0	37	7	1291.7	2350	675	961.7	2175	230	32.5	440	340
6	9	No	100	Yes	45.2	55	35	1150.0	1800	850	668.0	1200	335	655.0	750	575
6	9	No	100	No	129.0	205	88	840.0	900	700	329.0	400	215	625.0	700	550
6	9	No	100	Yes	16.2	25	5	495.0	800	260	241.7	450	110	279.2	330	175
6	9	No	100	Yes	42.6	60	23	471.0	600	385	42.6	60	23	471.0	600	385
6	11	No	100	Yes	392.0	950	75	1515.0	2500	775	1150.0	2500	190	1060.0	1600	750
6	11	No	90	Yes	231.3	975	30	1412.5	1575	1000	544.2	1100	190	1033.3	1650	850
6	11	No	100	No	85.2	260	33	1389.2	2200	650	626.7	800	410	876.7	1800	230
6	11	No	100	Yes	606.4	1050	220	1360.7	1750	1000	606.4	1050	220	1360.7	1750	1000
6	11	No	100	Yes	922.0	2300	370	1350.0	2500	850	922.0	2300	370	1350.0	2500	850
6	11	No	100	No	21.0	41	8	1312.5	1600	1000	824.2	1400	330	650.8	750	480
6	11	No	90	Yes	455.8	1425	60	1075.0	2400	450	788.3	2000	175	696.7	1550	325
6	11	No	100	Yes	6.8	12	3	1050.0	2100	500	367.6	1175	41	735.0	1000	600
6	11	No	100	Yes	47.6	220	5	1046.9	1500	650	443.1	1000	75	561.3	625	465
6	11	No	90	No	260.0	350	145	1034.4	1600	450	697.5	1300	250	590.0	775	320

Unfortunately, such minimal ambient lighting was not sufficient for adequate illumination of hard copy work at pupils' desks. Hence, reduction of image contrast on the IWB was unavoidable.

(1) With minimal ambient lighting (blinds closed, lights off), mean illuminance was low (198 ± 40 lux) and insufficient for adequate illumination of pupils' desks (Fig. 8). Room lights were needed in 70% of cases to give 35 cd m^{-2} at pupils' desks for use of hard copy (half the 70 cd m^{-2} recommended by CIBSE, 2004), reducing contrast on the IWB. According to lighting quality models (Rea, 1982, 1983), the reduced contrast causes a small but measurable reduction in visual performance.
(2) The presence of a visible reflective sheen on different IWBs decreased contrast depending on lighting condition. For example, with lights on and blinds open, the mean contrast for boards without a sheen (see Table 4) was 21% ± 3.8 whereas with a sheen, the mean contrast was lower at 18% ± 2, indicating the possible contribution of scattered light in reducing image contrast.

3.4. Pattern glare from window blinds

Roller blinds (34% of classrooms) and curtains (12% of classrooms) were not usually patterned in such a way as to induce pattern glare. Vertical blinds (6% of classrooms) had sections that were typically separated by about 0.1 m and did not have a spatial frequency within the appropriate range at viewing distances less than 6 m. Venetian blinds (Fig. 3) did, however, have an appropriate spatial frequency and were fitted in 23% of classrooms. The blinds differed in colour but were similar in size. The distance between slats averaged 43 ± 3 mm in a sample of six classrooms. The range of viewing distances from which the blinds had an appropriate spatial frequency was therefore 2.5–25 m. From a viewing distance of 2.5 m the blinds subtended more than 30° in most cases, more than sufficient in size to evoke glare. The duty cycle and contrast varied with orientation of the stripes relative to the viewer and to any source of directional light, but was typically in the range appropriate for inducing glare. This was the case even for blinds that were black and fully closed, because of a sheen on the curved surface. Positioning of desks and chairs suggested that pupils were often oriented facing the blinds.

3.5. Differences between schools and local authorities

There were significant differences between schools and local authorities with respect to the mean percentage of 100 Hz luminaires installed per classroom (Fig. 4), which ranged across schools

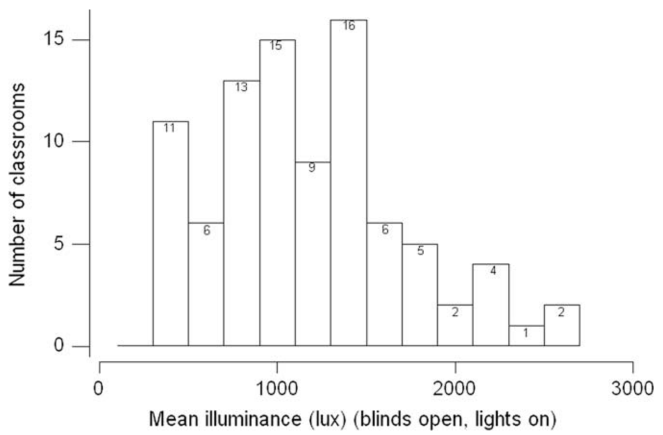

Fig. 5. Mean classroom illuminance with blinds open and lights on.

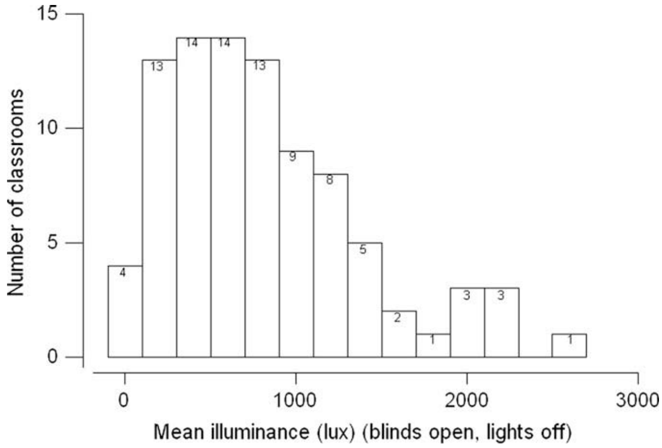

Fig. 6. Mean classroom illuminance with blinds open and lights off.

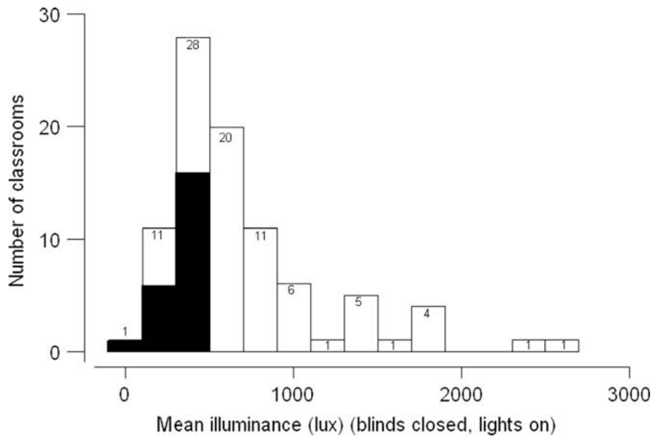

Fig. 7. Mean classroom illuminance with blinds closed (where possible) and lights on. Classrooms with functioning blinds (shaded) are distinguished from those which had one or more absent or faulty blinds (clear).

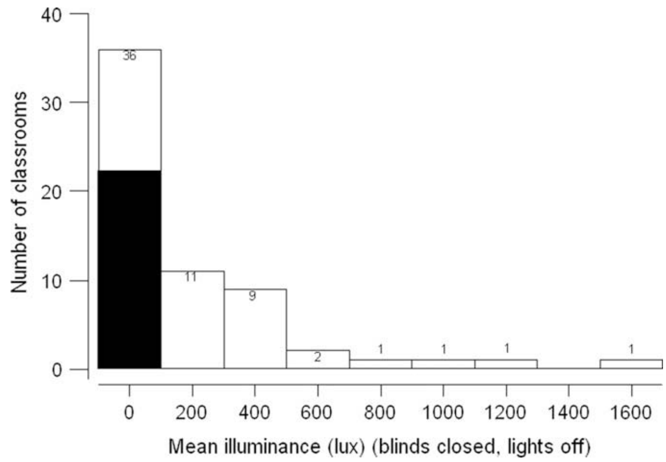

Fig. 8. Mean classroom illuminance with blinds closed (where possible) and lights off. Classrooms with functioning blinds (shaded) are distinguished from those which had one or more absent or faulty blinds (clear).

from 21% to 100% ($H_{(10)} = 27.7$, $p = 0.002$) and across local authorities from 30% to 96% ($H_{(5)} = 25.0$, $p < 0.001$). There were also significant differences in the mean illuminance, for example under artificial light, which ranged from 315 lux to 1321 lux across schools ($H_{(10)} > 18.72$, $p < 0.044$) and from 449 lux to 1145 lux across local authorities ($H_{(5)} = 16.54$, $p = 0.005$) (see Table 1).

4. Discussion

This study has demonstrated departure from best practice in classroom lighting. Current practice may impair performance and promote discomfort as a result of (a) imperceptible 100 Hz flicker from fluorescent lighting, and (b) glare from daylighting, fluorescent lighting, and data-projection screens such as IWBs and DWBs. There is also the possibility of pattern glare from some types of window blind. In the following sections, the findings are contextualised in relation to the established literature. The way in which the findings may contribute to understanding the outcomes of previous studies is examined. Such an examination does necessarily involve some speculation, the intention of which is to highlight possible foci for further studies. At the end of the paper, recommendations for best practice are provided.

4.1. *Imperceptible 100 Hz flicker in light from fluorescent lamps*

The prevalence of imperceptible 100 Hz flicker, which can impair visual performance, health and comfort (see Jaen et al., 2005; Veitch, 2005; Wilkins et al., 1989), is surprising. Luminaires with high frequency electronic control circuitry can avoid these problems, and have been available for about 20 years. Indeed, CIBSE (2004) and DfEE (1999) actually recommend installation of high frequency electronic control circuitry in classrooms. Its prevalence is also unfortunate, as younger individuals show relatively high sensitivity (Lindner & Kropf, 1993), consistent with their higher critical fusion frequency (CFF) – the maximum rate at which intermittent light can be perceived as flicker; individuals with higher CFF values are more likely to complain about 100 Hz flicker (Brundrett, 1974).

The prevalence of imperceptible 100 Hz flicker from fluorescent lighting may explain teachers' and pupils' preferences for

Fig. 9. Typical classroom with interactive whiteboard and data-projector.

Fig. 10. Visible sheen on an interactive whiteboard (Brand 2).

Table 2
Mean whiteboard luminance (cd m^{-2}) in each classroom measured under lighting conditions shown.

IWB or DWB	IWB brand	Sheen visible	Luminance (cd m^{-2})			
			Blinds open, lights on	Blinds open, lights off	Blinds closed, lights on	Blinds closed, lights off
IWB	1	No	482	447	415	
IWB	1	No	264	183	204	
IWB	1	No	244	200	224	
IWB	1	No	414	341	383	
IWB	1	No	286	261		
IWB	1	No	287	257	240	222
IWB	1	No	412	391	318	287
IWB	1	No	246	211	236	205
IWB	1	No	515	468	191	168
IWB	1	No	554	487	122	63
IWB	1	No	703	675	384	343
IWB	1	No	193	147	133	99
IWB	1	No	281	244	248	223
IWB	2	Yes	2121	2082	2027	
IWB	2	Yes	1626	1593	1566	
IWB	2	Yes	1162	1117		
IWB	2	Yes	812	783	801	
IWB	2	Yes	657	500	582	
IWB	2	Yes	1623	1645	1641	1463
IWB	2	Yes	2322	2208	2247	2123
IWB	2	Yes	2357	2245	2108	2036
IWB	2	Yes	2348	2348	2290	2244
IWB	2	Yes	2574	2471	2564	2476
IWB	2	Yes	2795	2936	2930	2773
IWB	3	Yes	658	529	632	498
IWB	3	Yes	3427	3265	3412	3233
IWB	3	Yes	509	423	442	374
IWB	4	Yes	1004	849	970	847
IWB	4	Yes	904	863	844	806
IWB	5	Yes	793	754		
IWB	6	Yes	269	238	244	201
IWB	6	Yes	953	935	888	859
IWB	6	Yes	563	337	311	243
IWB	7	Yes	730	655	642	583
DWB		Yes	16,003	17,608	15,970	
DWB		Yes	42,300	44,277	52,450	
DWB		Yes	55,597	54,233		
DWB		Yes	13,350	16,310	18,747	
DWB		Yes	12,670	12,297		
DWB		Yes	12,247	13,180	12,683	
DWB		Yes	6046	5990	5908	
DWB		Yes	130,200	118,300	125,733	
DWB		Yes	2149	2031	2021	
DWB		Yes	106,200	106,467	94,853	96,560
DWB		Yes	32,343	31,037	32,623	31,573
DWB		Yes	24,337	23,593	22,637	24,120
DWB		Yes	22,857	23,820	21,670	22,577
DWB		Yes	324,033	298,533	329,633	299,867
DWB		Yes	32,877	31,640	33,550	32,570
DWB		Yes	72,943	64,813	70,800	60,497

daylighting (Galasiu & Veitch, 2006; Hathaway, 1983), and why teachers prefer to control the balance between fluorescent and daylighting (Lang, 2002). Differences in behaviour under fluorescent lighting (Fenton & Penney, 1985; Treichel, 1974) may also be relevant; if the 100 Hz flicker inhibits pupils' task performance, and causes headache, a concomitant reduction in motivation and increase in 'off-task' behaviour may be expected. Reports of enhanced learning and attainment under daylighting may have a similar explanation (Heschong & Knecht, 2002; Heschong et al., 1999). The increase in repetitive behaviours among autistic children (Fenton & Penney, 1985) is also explicable in these terms. Autistic individuals have recently been shown to have greater sensitivity to light and to respond to spectral filters (Ludlow, Wilkins, & Heaton, 2006).

Examining these relationships in more detail is a focus for further research. However, given this study's findings, exploitation of daylight, rather than 100 Hz fluorescent light, appears to be an appropriate strategy for teachers to minimize effects of imperceptible flicker, subject to avoiding excessive illuminance (see below). Given that the extent of 100 Hz lighting differed between schools and local authorities, installation of classroom lighting appears to be affected by misguided policy decisions. The high frequency fluorescent lighting does not have the effects explored above, uses less energy and has lower long-term running costs (Berman, 2003; Clanton, 1999; Murphy, 1999); although unit costs are higher, pay-back time is only a few years. Indeed, CIBSE (2004) sustainability recommendations themselves encourage the use of high frequency lighting to increase efficiency.

4.2. Illuminance at pupils' desks

Compared to recommendations (CIBSE, 2004), illuminance varied from inadequate to excessive. The latter was caused by both

Table 3
The Michelson contrast (%), and luminance (cd m^{-2}) away from the glare spot, on (a) interactive whiteboards (IWB) and (b) dry-wipe white boards (DWB).

		Contrast (%) and mean luminance (cd m^{-2}) ± standard error		
		Open	Closed (all classrooms)	Closed (classrooms with functioning blinds)
(a) IWB				
Lights	On	19% ± 2 260.4 ± 18.1 N = 34	32% ± 3 166.9 ± 11.3 N = 31	30% ± 3 153.6 ± 13.0 (N = 19)
	Off	30% ± 3 210.9 ± 18.7 N = 34	55% ± 4 116.6 ± 12.7 N = 23	58% ± 4 102.8 ± 11.5 (N = 14)
(b) DWB				
Lights	On	29% ± 3 267.3 ± 19.3 N = 16	40% ± 4 212.7 ± 17.7 N = 14	36% ± 7 196.6 ± 26.4 (N = 6)
	Off	46% ± 5 210.9 ± 16.7 N = 16	64% ± 6 161.1 ± 19.7 N = 7	50% ± 12 151.7 ± 24.1 (N = 2)

Table 4
The Michelson contrast away from the glare spot.

IWB or DWB	IWB brand	Sheen visible	Michelson contrast			
			Blinds open, lights on	Blinds open, lights off	Blinds closed, lights on	Blinds closed, lights off
IWB	1	No	0.374	0.437	0.627	
IWB	1	No	0.094	0.160	0.180	
IWB	1	No	0.351	0.497	0.460	
IWB	1	No	0.180	0.259	0.209	
IWB	1	No	0.292	0.440		
IWB	1	No	0.306	0.421	0.622	0.849
IWB	1	No	0.191	0.251	0.520	0.792
IWB	1	No	0.420	0.701	0.479	0.772
IWB	1	No	0.030	0.049	0.435	0.610
IWB	1	No	0.004	0.005	0.107	0.240
IWB	1	No	0.078	0.087	0.391	0.594
IWB	1	No	0.170	0.235	0.290	0.632
IWB	1	No	0.293	0.451	0.435	0.607
IWB	2	Yes	0.209	0.252	0.412	
IWB	2	Yes	0.169	0.237	0.422	
IWB	2	Yes	0.340	0.636		
IWB	2	Yes	0.099	0.157	0.154	
IWB	2	Yes	0.046	0.091	0.110	
IWB	2	Yes	0.164	0.135	0.209	0.491
IWB	2	Yes	0.208	0.394	0.270	0.622
IWB	2	Yes	0.260	0.383	0.344	0.653
IWB	2	Yes	0.254	0.317	0.390	0.627
IWB	2	Yes	0.220	0.174	0.280	0.451
IWB	2	Yes	0.142	0.198	0.232	0.588
IWB	3	Yes	0.233	0.533	0.282	0.847
IWB	3	Yes	0.191	0.388	0.308	0.441
IWB	3	Yes	0.185	0.320	0.258	0.509
IWB	4	Yes	0.394	0.600	0.477	0.585
IWB	4	Yes	0.173	0.180	0.284	0.287
IWB	5	Yes	0.204	0.630		
IWB	6	Yes	0.098	0.104	0.202	0.564
IWB	6	Yes	0.071	0.100	0.175	0.161
IWB	6	Yes	0.001	0.064	0.017	0.212
IWB	7	Yes	0.150	0.254	0.293	0.505
DWB		Yes	0.284	0.358	0.491	
DWB		Yes	0.511	0.666	0.634	
DWB		Yes	0.388	0.686		
DWB		Yes	0.139	0.191	0.180	
DWB		Yes	0.363	0.736		
DWB		Yes	0.190	0.244	0.316	
DWB		Yes	0.169	0.419	0.208	
DWB		Yes	0.405	0.503	0.620	
DWB		Yes	0.080	0.282	0.369	
DWB		Yes	0.434	0.607	0.505	0.849
DWB		Yes	0.226	0.233	0.406	0.613
DWB		Yes	0.220	0.432	0.304	0.624
DWB		Yes	0.340	0.435	0.415	0.601
DWB		Yes	0.318	0.569	0.327	0.659
DWB		Yes	0.471	0.669	0.518	0.771
DWB		Yes	0.174	0.274	0.237	0.379

by excessive artificial lighting and also poor control of daylighting, owing to absence or malfunction of blinds. Excessive illuminance can cause discomfort and disability glare (Kim & Koga, 2005; Osterhaus, 2005). There is evidence for a downturn in comfort at the high lighting levels measured in this study (Rea, 1982, 1983), although it is important to note that ratings of discomfort are very variable (Osterhaus, 2005), and may depend on the user and task (Galasiu & Veitch, 2006). It is also important to note that data were collected in the summer months, when illumination from daylighting may have been higher than average across the year. It is not possible to dismiss entirely the potential effect of increased summer illumination. In the UK, schools are in operation for about six weeks of summer (from the start of June to mid-July), with climate tending to be fairly stable during June, July and August. However, the percentage cloud cover measured immediately before recording data in each classroom (mean = 64%; median = 90%), and the proportion of classroom measurements during which the sun was visible (only 45%) (see Table 1) may indicate that the findings from this study in particular would have been apparent at other times of year, and not only during the summer months. Indeed, as indicated above, mean illuminance in classrooms was not significantly related to percentage cloud cover, or whether the sun was visible.

Unnecessarily high illumination at pupils' desks was frequently a result not only of daylight but also of fluorescent lighting. Often lighting levels were excessive when blinds were drawn; fluorescent lighting was needed for adequate illumination at desks with minimal daylighting (often far from windows), but for desks that were adequately daylit, the extra lighting simply added to excess illuminance. This large scale, unnecessary use of fluorescent lighting directly contradicts both UK national guidelines, and sustainability recommendations in the CIBSE (2004) code.

In addition, user comfort decreases if the ratio between maximum and minimum illuminance in the same room exceeds 0.6 (Slater et al., 1993). Hence, separate control of fluorescent lighting in different classroom areas is important. Unfortunately, the extent to which this was possible was very variable. Blinds and other daylight controls are also important, but exclusive dependence on artificial lighting is not to be advised, not only because of the flicker mentioned above but also because it may disrupt hormone production and circadian rhythms (Küller & Lindsten, 1992).

High illuminance may explain why teachers favour soft lighting, and have observed improved behaviour under dim lighting (Dinsmore, 2003; Estes, 1984). If disability and discomfort glare caused by excessive illuminance inhibit task performance and cause discomfort, 'off-task' behaviour may be a consequence of both. Again, these issues are a focus for further research.

Even if teachers had more control over day- and fluorescent lighting, user judgments of illuminance are often inaccurate, particularly further from windows. Use of blinds to regulate daylight is rarely based on current illuminance, but more on perceptions developed over time (Galasiu & Veitch, 2006). Hence, automatic lighting control may be a sensible alternative, but was only observed in two classrooms at one school.

4.3. Luminance and glare from data-projection screens

Luminance of the glare spot from whiteboards was of an intensity that can induce discomfort. Although discomfort thresholds vary between individuals (Osterhaus, 2005), luminance was in excess of recommendations for paper (70 cd m^{-2}), and of user preferences (45–105 cd m^{-2}, van Ooyen, van de Weijgert, & Begemann, 1987). Maximum luminance recorded from one DWB was so high as to approach hazardous levels (Wu, Seregard, & Algvere, 2006). Disability glare was also a problem, and was caused both by (1) the glare spot itself, and (2) reflected ambient light.

(1) The extent of disability glare varied according to the ratio of specular to diffuse reflection. This differed between boards with and without a visible sheen, as did luminance within the glare spot. Brands with a visible sheen were those compatible with dry-wipe markers, requiring a smoother surface for removal of marker pen residue (DWBs had the most intense sheen). This reduced contrast of the projected image almost by half, whilst boards incompatible with dry-wipe markers provided more diffuse reflection, little visible sheen, and minimal reduction in contrast within the glare spot.
(2) Maximum image contrast, with room lights off and blinds closed, was almost twice that with room lights on. Recommended luminance of hard copy for reading and writing is 70 cd m^{-2}. In this study, room lighting was needed in 70% of classrooms to bring luminance of hard copy at pupils' desks to just half that level. Unfortunately, increasing room lighting reduced whiteboard contrast, causing disability glare. This effect was most apparent on whiteboards with a visible sheen.

These findings may account for pupils' complaints about visibility of data-projection screens (Hall & Higgins, 2005; Smith et al., 2005). Presence of a visible sheen should inform purchasing decisions; it indicates a higher ratio of specular to diffuse reflection, and the extent to which ambient lighting and the glare spot will decrease comfort and visibility. Reduced expense of installing only a data-projector and using it with a conventional DWB appears to provide many of the pedagogical benefits of an IWB (Glover, Miller, Averis, & Door, 2005; Smith et al., 2005). However, such a practice causes intense glare because of the greater sheen, and should be avoided.

Of course, many teachers already work with vertically wall-mounted whiteboards with a visible sheen. Such boards should be remounted such that they tilt away from the wall by 5–10° at the base, so the specular component of reflection is directed towards the ceiling. This solution appears so obvious that it is surprising the manufacturers' instructions specify vertical mounting. If remounting is impossible, lowering contrast between the glare spot and the background will reduce discomfort and disability glare. One approach would be to use a coloured or black background.

Although we cannot necessarily generalise our findings and recommendations to standard computer display equipment, similar problems have been identified in the past with conventional computer screens (e.g. Blehm, Vishnu, Khattak, Mitra & Yee, 2005; CIBSE, 2004). Given our findings for whiteboards, it would be valuable in further work to examine the ratio of specular to diffuse reflection from conventional computer displays in school classrooms, and approaches to ameliorate any resultant glare.

4.4. Pattern glare from window blinds

Recently, it has become clear that patterns can be a source of discomfort glare (Harle et al., 2006; Wilkins, 1995). The conditions under which glare is experienced are still under study, but use of large patterned surfaces with repetitive stripes, having spatial characteristics appropriate for induction of pattern glare, is to be discouraged. Venetian blinds (23% of classrooms) were of a spatial frequency appropriate for induction of pattern glare, and are best avoided in classrooms.

4.5. Reading through coloured overlays

The findings may explain some of the beneficial effects of coloured overlays. These are spectral filters placed upon the page through which pupils read. Such filters increase reading speed and reduce symptoms of visual stress and headaches (see Wilkins, 2003 for review). The overlays reduce luminance of the page by a factor of about two. According to the data collected in the present study, this would reduce luminance to recommended levels in an additional 24% of classrooms lit with daylight and fluorescent lighting, and may be expected to improve comfort and task performance.

100 Hz fluorescent lighting fluctuates not only in luminance, but also in chromaticity (colour) due to differences in the persistence of the component phosphors in the fluorescent lamps. The variation depends on lamp type and may be such as to activate colour-opponent pathways (Wilkins & Clark, 1990). Spectral filters such as overlays can

Fig. 11. Windows without functional blinds preclude teachers' regulation of illumination.

reduce the variation in chromaticity and may therefore reduce activation of neurons within the visual system responding to 100 Hz modulation. These interpretations are compatible with explanations framed around cortical hyperexcitability (Wilkins, 2003).

4.6. Conclusions and recommendations

This study has identified a number of problematic aspects of classroom lighting. Most of these problems are unnecessary and appear due to poor policy decisions. In most cases, action to correct the problems would be simple, and any costs would be offset in the medium term, due to increased efficiency, reduction of wastage, and benefits in terms of health of pupils and staff.

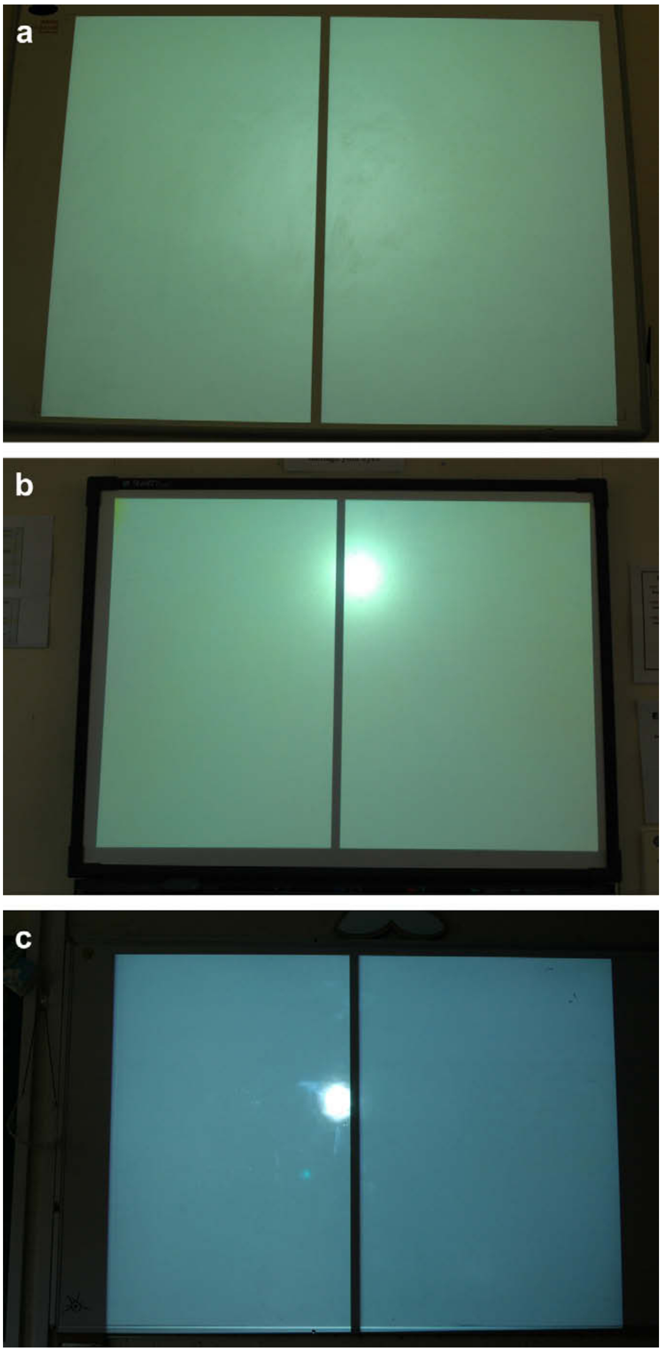

Fig. 12. Glare spot on (a) Brand 1 interactive whiteboard (with least visible sheen), (b) Brand 2 interactive whiteboard (with more visible sheen), and (c) dry-wipe whiteboard (with most visible sheen).

1. Classrooms are lit with an unnecessarily inefficient form of fluorescent lighting that has been shown to cause headaches and impair visual performance. Schools should consider replacing low frequency ballast with high frequency control circuitry. Combinations of low frequency and lamps with a high colour temperature (e.g. 6000 K) in particular should be avoided because the phosphors have short persistence and give high modulation (Wilkins & Clark, 1990); lamps with colour temperature of 3500 K should be used instead.
2. Classrooms are over-lit with excessive fluorescent lighting and excessive daylight. Such overlighting may vary between different parts of the classroom; in many of the classrooms studied, neither artificial light nor daylight could adequately be controlled (e.g. through absent or malfunctioning blinds; see Fig. 11). To compensate, newly built classrooms should have automatically dimming luminaries, provided these are flicker free. If replacement of fixtures in this way in existing classrooms is too expensive, switching should be modified to enable greater teacher control of lighting levels in different parts of the classroom. Likewise, blinds should be installed or regularly maintained, and enable maximum versatility for teachers in regulating lighting levels close to windows. Teachers should be provided with a way of assessing lux levels, rather than working solely on intuitive assessment of lighting levels, which as discussed earlier, tend not be accurate.
3. Glare from IWBs and DWBs is common. Pattern glare from Venetian blinds is a possibility. In existing fixtures, IWBs and DWBs should be retrospectively tilted away from the wall by 5–10° at the base, so the specular component of reflection is directed towards the ceiling and the effects of glare are reduced. The amount of glare was related to the extent to which the IWB or DWB had a visible sheen (see Fig. 12). When making purchasing decisions, data-projectors should **never** be installed with a DWB unless it is tilted as described. Indeed, projection onto a matt white or light-coloured wall would be preferable. In the same way, IWBs should also be inspected for the extent of visible sheen, and purchasing decisions made on that basis. Glare from incident sunlight on the IWB or DWB is also a problem; blinds should be installed to negate such effects at all viewing positions during the day.

Appendix 1. Description of classrooms.

Classroom length (m)	Mean = 9.4, $N = 87$, SD = 3.0
Classroom width (m)	Mean = 7.5, $N = 87$, SD = 1.2
Floor area (m^2)	Mean = 71.9, $N = 87$, SD = 33.0
Classroom length/width	Mean = 1.2, $N = 87$, SD = 0.3
Number of luminaires per classroom	Mean = 10.5, $N = 90$, SD = 3.8
Window area (m^2)	Mean = 17.9, $N = 90$, SD = 23.1
Window area/floor area	Mean = 0.28, $N = 87$, SD = 0.41
Proportion of classrooms with window on longest side	81% ($N = 87$)
Proportion of classrooms with window in one wall	47% ($N = 87$)
Proportion of classrooms with window in two walls	51% ($N = 87$)
Proportion of classrooms with window in three walls	2% ($N = 87$)

References

Baccino, T., Jaschinski, W., & Bussolon, J. (1999). Exploring the flicker effect: the influence of in-flight pulsations on saccadic control. *Vision Research, 41*, 3909–3916.

Berman, S. M., Greenhouse, D. S., Bailey, I. L., Clear, R. D., & Raasch, T. W. (1991). Human electroretinogram responses to video displays, fluorescent lighting, and other high-frequency sources. *Optometry and Vision Science, 68*(8), 645–662.

Berman, T. (2003). Purchasing and selecting school lighting. *School Planning & Management, 42*(1), 21–22.

Blehm, C., Vishnu, S., Khattak, A., Mitra, S., & Yee, R. W. (2005). Computer vision syndrome: a review. *Survey of Ophthalmology, 50*(3), 253–262.

Brundrett, G. W. (1974). Human sensitivity to flicker. *Lighting Research and Technology, 6*(3), 127–143.

CIBSE. (2004). *Code for lighting*. London: CIBSE.

Clanton, N. (1999). Lighting the school of the future. *School Planning and Management, 38*(12), 33–35.

Csíkszentmihályi. (1990). *Flow: The psychology of optimal experience*. New York: Harper and Row.

Dakin, E. R. G., Hargroves, R. A., Ruddock, K. H., & Simons, A. H. (1994). *Visual sensitivity to physiologically high frequency flicker*. Paper presented at the 1994 CIBSE National Lighting Conference, UK.

DfEE. (1999). *Lighting design for schools, Vol. 90*. London: The Stationery Office.

DfES. (2004). *Guidance for the interactive whiteboards funding 2004–2005: Aims of the initiative*. London: DfES.

Dinsmore, T. S. (2003). *Classroom management*. Michigan, USA.

Dyck, J. (2002). The built environment's effect on learning: applying current research. *Montessori Life, 14*(1), 53–56.

Estes, R. C. (1984). Quality lighting for the learning environment. *School Business Affairs, 50*(1), 44–45.

Eysel, U. T., & Burandt, U. (1984). Fluorescent tube light evokes flicker responses in visual neurons. *Vision Research, 24*(9), 943–948.

Fenton, D. M., & Penney, R. (1985). The effects of fluorescent and incandescent lighting on the repetitive behaviours of autistic and intellectually handicapped children. *Australia and New Zealand Journal of Developmental Disabilities, 11*(3), 137–141.

Fisher, R. S., Harding, G., Erba, G., Barkley, G. L., & Wilkins, A. (2005). Photic- and pattern-induced seizures: a review for the epilepsy foundation of America working group. *Epilepsia, 46*(9), 1426–1441.

Galasiu, A. D., & Veitch, J. A. (2006). Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review. *Energy and Buildings, 38*(7), 728–742.

Glover, D., Miller, D., Averis, D., & Door, V. (2005). The interactive whiteboard: a literature survey. *Technology, Pedagogy and Education, 14*(2), 155–170.

Hall, I., & Higgins, S. (2005). Primary school students' perceptions of interactive whiteboards. *Journal of Computer Assisted Learning, 21*(2), 102–117.

Harle, D. E., Shepherd, A. J., & Evans, B. J. W. (2006). Visual stimuli are common triggers of migraine and are associated with pattern glare. *Headache, 46*, 1431–1440.

Hathaway, W. E. (1983). Lights, windows, color: elements of the school environment. In *59th Annual meeting of the Council of Educational Facility Planners* (p. 28). Alberta, Canada.

Hathaway, W. E. (1994). Non-visual effects of classroom lighting on children. *Educational Facility Planner, 32*(3), 12–16.

Heschong, L., & Knecht, C. (2002). Daylighting makes a difference. *Educational Facility Planner, 37*(2), 5–14.

Heschong, L., Mahone, D., Kuttaiah, K., Stone, N., Chappell, C., McHugh, J., et al. (1999). *Daylighting in schools: An investigation into the relationship between daylighting and human performance*. San Francisco: Pacific Gas and Electric Company.

Jaen, M., & Kirschbaum, C. F. (2001). Flicker and visual performance: a psychological experiment with fluorescent lamps. *Perception, 30*, 60–61.

Jaen, M., Sandoval, J., Colombo, E., & Troscianko, T. (2005). Office workers' visual performance and temporal modulation of fluorescent lighting. *Leukos, 1*(4), 27–46.

Kim, W., & Koga, Y. (2005). Glare constant Gw for the evaluation of discomfort glare from windows. *Solar Energy, 78*(1), 105–111.

Küller, R., & Laike, T. (1998). The impact of flicker from fluorescent lighting on well-being, performance and physiological arousal. *Ergonomics, 41*(4), 433–447.

Küller, R., & Lindsten, K. (1992). Health and behaviour of children in classrooms with and without windows. *Journal of Environmental Psychology, 12*, 305–317.

Lang, D. C. (2002). *Teacher interactions within the physical environment: How teachers alter their space and/or routines because of classroom character*. Seattle: University of Washington.

Lindner, H., & Kropf, S. (1993). Asthenopic complaints associated with fluorescent lamp illumination (FLI): the role of individual disposition. *Lighting Research and Technology, 25*(2), 59–69.

Ludlow, A. K., Wilkins, A. J., & Heaton, P. (2006). The effect of coloured overlays on reading ability in children with autism. *Journal of Autism and Developmental Disorders, 36*(4), 507–516.

Lyons, J. B. (2002). The learning environment: do school facilities really affect a child's education? *Learning by Design, 11*, 10–13.

Murphy, P. (1999). What you need to know about classroom lighting. *School Planning and Management, 38*(4), 52–55.

van Ooyen, M. H. F., van de Weijgert, J. A. C., & Begemann, S. H. A. (1987). Preferred luminances in offices. *Journal of the Illuminating Engineering Society, 16*, 152–156.

Osterhaus, W. K. E. (2005). Discomfort glare assessment and prevention for daylight applications in office environments. *Solar Energy, 79*(2), 140–158.

Rea, M. S. (1982). An overview of visual performance. *Lighting Design and Application, 12*(11), 35–41.

Rea, M. S. (1983). Effects of Haidinger's brushes on visual performance. *Journal of the Illuminating Engineering Society, 12*(3), 197–203.

Rittner, H., & Robbin, M. (2002). Color and light in learning. *School Planning & Management, 41*(2), 57–58.

Schneider, M. (2003). *Linking school facility conditions to teacher satisfaction and success*. Washington, DC: National Clearinghouse for Educational Facilities.

Schreiber, M. E. (1996). Lighting alternatives: considerations for child care centres. *Young Children, 51*(4), 11–13.

Schulz, J. (1977). Lighting and the learning space. *OSSC Bulletin, 21*(2), 43.

Shapiro, M., Roth, D., & Marcus, A. (2001). The effect of lighting on the behavior of children who are developmentally disabled. *Journal of International Special Needs Education, 4*, 19–23.

Slater, A. I., Perry, M. J., & Carter, D. J. (1993). Illuminance differences between desks: limits of acceptability. *Lighting Research and Technology, 25*, 91–103.

Smith, H. J., Higgins, S., Wall, K., & Miller, J. (2005). Interactive whiteboards: boon or bandwagon? A critical review of the literature. *Journal of Computer Assisted Learning, 21*, 91–101.

Smith, S. W., & Rea, M. S. (1980). Relationships between office task performance and ratings of feelings and task evaluations under different light sources and levels. CIE Publication No. 50, pp. 207–211.

Treichel, A. J. (1974). School lights and problem pupils. *Science News, 105*(16), 258–259.

Veitch, J. A. (2005). Light, lighting, and health: issues for consideration. *Leukos, 2*(2), 85–96.

Wilkins, A. (1980). Visually-induced seizures. *Progress in Neurobiology, 15*, 85–117.

Wilkins, A. (1986). Intermittent illumination from visual-display units and fluorescent lighting affects movements of the eyes across text. *Human Factors, 28*(1), 75–81.

Wilkins, A. (1995). *Visual stress*. Oxford: Oxford University Press.

Wilkins, A. (2003). *Reading through colour*. Chichester: Wiley.

Wilkins, A., & Clark, C. (1990). Modulation from fluorescent lamps. *Lighting Research and Technology, 22*(2), 103–109.

Wilkins, A., Nimmo-Smith, M. I., Slater, A., & Bedocs, L. (1989). Fluorescent lighting, headaches and eyestrain. *Lighting Research and Technology, 21*(1), 11–18.

Woolner, P., Hall, E., Higgins, S., McCaughey, C., & Wall, K. (2007). A sound foundation? What we know about the impact of environments on learning and the implications for Building Schools for the Future. *Oxford Review of Education, 33*(1), 47–70.

Wu, J., Seregard, S., & Algvere, P. V. (2006). Photochemical damage of the retina. *Survey of Ophthalmology, 51*(5), 461–480.